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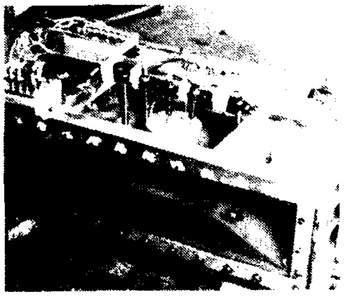

GEOTECHNICAL LABORATORY

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LARGE CENTRIFUGE: A CRITICAL ARMY CAPABILITY FOR THE FUTURE

Compiled and Edited

by

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This report presents an overview of potential applications of a proposed US Army Engineer Waterways Experiment Station (WES) centrifuge for the purposes of research and development. Centrifuge testing applications correspond with the technical areas representative of the research conducted by the five laboratories and the Coastal Engineering Research Center of WES, and the Cold Regions Research Engineering Laboratory. The broad technical research areas discussed are (a) coastal, (b) cold regions, (c) environmental, (d) geotechnical, (e) hydraulic, and (e) structural. This report discusses those areas where centrifuge testing would greatly benefit research objectives particularly in cases where prototype data are very expensive if not impossible to acquire.

Centrifuge testing offers cost effective technology to address military and civil problem areas. Among many advantages and benefits of a centrifuge to the Corps of Engineers are (a) for complex problems for which calculation methods are not completely reliable or adequate, prototype behaviors can be

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predicted, (b) numerical methods can be validated, improved, or developed based on realistic prototype behavior, and (c) centrifuge tests can be used for parameter studies to investigate particular properties and behaviors in relation to variations in loads and boundary conditions. Centrifuge testing will allow the economical proof testing of designs, investigation of problem areas, and validation of numerical methods that have been prohibitively expensive to study with prototype testing. Also, centrifuge testing will allow the study of important behavior phenomena, including failure, that are impractical or not feasible to induce in prototype situations or for complex problems.

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Centrifuge testing	Geotechnical research
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Cold regions research	Soil-structure interaction research
Environmental research	Structural research

PREFACE

This report was compiled and edited by Mr. Richard H. Ledbetter, Earthquake Engineering and Geosciences Division, Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES). The authors of this report are Dr. S. A. Hughes, Coastal Engineering Research Center (CERC), WES; Dr. S. A. Ketcham, Cold Regions Research and Engineering Laboratory (CRREL); Drs. M. P. Rollings and C. R. Lee, Environmental Laboratory (EL), WES; Messrs. P. A. Gilbert and R. H. Ledbetter, GL. WES; Mr. M. B. Boyd and Dr. S. T. Maynord, Hydraulics Laboratory (HL), WES; Messrs. R. L. Mosher and H. W. Jones, Information Technology Laboratory (ITL), WES; and Mr. L. K. Davis and Dr. B. Rohani, Structures Laboratory (SL), WES. General supervision was by Dr. William F. Marcuson III, Chief, GL; Dr. James R. Houston, Chief, CERC; Dr. Lewis E. Link, Technical Director, CRREL; Dr. John Harrison, Chief, EL; Mr. Frank A. Herrmann, Jr., Chief, HL; Dr. N. Radhakrishnan, Chief, ITL; Mr. Bryant Mather, Chief, SL; and Dr. Dennis R. Smith, Assistant Technical Director, WES. The report was edited by Mrs. Joyce H. Walker, Information Management Division, Information Technology Laboratory, WES. Critical reviews and comments were provided by Mr. G. P. Hale, GL.

COL Larry B. Fulton, EN, was Commander and Director of WES during the publication of this report. Dr. Robert W. Whalin was Technical Director.

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LARGE CENTRIFUGE: A CRITICAL ARMY CAPABILITY FOR THE FUTURE

PART I: INTRODUCTION

1. The purpose of this report is to present an overview of potential applications of a proposed US Army Engineer Waterways Experiment Station (WES) centrifuge for the purposes of research and development. Centrifuge testing applications discussed in this report correspond with the technical areas representative of the research conducted by the five laboratories and the Coastal Engineering Research Center of WES and the Cold Regions Research and Engineering Laboratory. The technical areas discussed are (a) coastal, (b) environmental, (c) geotechnical, (d) hydraulic, (e) structural, and (f) cold regions. This report discusses those areas where centrifuge testing would greatly benefit research objectives, particularly in cases where prototype data are very expensive if not impossible to acquire.

2. The primary reasons that centrifuge testing has not played a major role in US civil engineering research activities to date are:

<u>a</u>. Centrifuge testing in the United States during the past 5 years is just becoming a major testing technique, although it has been widely used in engineering applications and research for 30 years in England and for more than 50 years in the Soviet Union. In the past 5 years, major centrifuge centers have been developed in France, Italy, Germany, Holland, and Japan.

<u>b</u>. Only within the last 10 years have large (equal to or greater than 100 g-ton*) centrifuges become available in the United States--at the University of Colorado, Boulder; University of California, Davis; and this year at Rensselaer Polytechnic Institute, Troy, NY. Therefore, the US universities are still in a learning environment with respect to centrifuge experiments. Large centrifuges are desirable to provide for better control of boundary effects and physical size of models, maximum instrumentation with least disruptive effects, and acquisition of better data on behavior and processes occurring in a test.

<u>c</u>. For militarily classified studies, there are few, if any, secure facilities where the Corps could conduct extensive and uninterrupted testing programs.

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* In this report, the method used to classify centrifuges is based on the capacity measured in g-tons, calculated by multiplying the maximum acceleration level, in multiples of Earth's gravity acceleration, with the weight of the maximum payload at that acceleration.

3. The presently proposed WES centrifuge would be the most powerful in the world at the design maximum force of 772 g-ton. Maximum payload would be 6.6 tons at 100-g centrifugal acceleration. The maximum centrifugal acceleration would be 350 g with a payload of 2.2 tons. A dynamic loading capability equivalent to a shaking table carrying 4.5 million tons of payload is proposed for investigating dynamic and earthquake problems. The centrifuge and test containers could also be used for explosive studies. Prototype dimensions of the payload platform at 350-g acceleration would be 578 m by 455 m with a maximum usable height of 805 m. The following examples typify the scale of problems that could be investigated:

a. A centrifuge container could hold combinations of soil, rock, and water for tests on such as fluid migration, geologic structures, geotechnical investigations, or sea overlying seabed. The facility could model 500 years of pollutant or heat migration in 1.5 days.

b. Penetrometer tests and particle size effects could be studied in a model simulating a prototype of 260-m diam by 200 m deep at 200-g acceleration. A penetrometer, pile group, or deep foundation could be loaded to hundreds of tons at 350-g acceleration.

c. Earthquake shaking could be conducted modeling a section of a dam or embankment with a cross section of 360 m, 60 m deep, and 120 m along the crest (i.e., a full cross section of an earth dam such as Sardis could be modeled).

d. Fluid flow and transport could be studied by modeling a test field of 455-m diam and 255 m deep at 350-g acceleration.

e. Deep foundations, seabeds, and piles in a test field having a 455-m diam and more than 200-m depth could be modeled at 350-g acceleration.

General Discussion

4. Phenomena in mechanics are determined by a combination of dimensional quantities such as stress, density, and energy which take on specific numerical values under certain conditions. Problems in mechanics are solved by determining appropriate functions and parameters using relevant laws of nature along with geometrical relations combined in functional equations, usually differential equations. In purely theoretical investigations, equations are used to establish the kinematics of the system under analysis and to calculate unknown physical quantities using numerical techniques. However, mathematical difficulties are sometimes too great to permit solution of a

problem solely by the processes of analysis and calculation even when simplifying assumptions are made. Often, the problem cannot be mathematically formulated because the mechanical phenomenon to be investigated is too complex to be described by a satisfactory model and the forces in the equations of motion are unknown. When mathematical formulation is impossible, physical modeling must be considered for the solution of engineering problems.

5. Physical modeling is a well-known approach to solving engineering problems so complex that they are not amenable to exact mathematical solution and was the original reason for the creation of the US Army Engineer Waterways Experiment Station. An example of such a problem might be that of a three-dimensional system with nonlinear material properties, complex boundary conditions, and time-dependent phenomena. Obviously, the state of stress in a small scale model under normal self-weight (gravity) loading will be much different from the state of stress in a full size prototype. If the model materials have stress-dependent constitutive behavior and exhibit time-dependent response phenomena, quantitative and even qualitative differences in behavior might be expected between a small scale model and the corresponding full size prototype (i.e., the model is distorted and where the effects of these distortions are significant, tests at 1 g of small scale models are misleading unless the nature of the effects of the distortions are well understood). This is to say that, unless measures are taken in the small scale modeling, not only will measurable parameters such as stress, deformation, pressure, and time for processes in the model be different from those in the prototype, but the observed response or failure mechanism may also be quite different in the model than in the prototype.

6. However, if a small scale model could be placed in a field where acceleration could be increased so that stress level caused by self-weight in the model would be the same as the corresponding stress level existing in the prototype and time-dependent phenomena could be controlled, many of the problems and limitations associated with testing a small scale model would be removed. Acceleration above normal gravity (1 g) is achieved through the use of a centrifuge, and in the elevated gravity field, model behavior (response to imposed conditions) will theoretically be directly correlated with that of the full sized prototype if the experiment has been designed properly (i.e., similitude exists between model and prototype in terms of geometry, material properties, applied stresses, and time).

7. The primary advantages of a centrifuge test are that model stresses and strains can be made equal to those of the prototype, and extrapolation of model results to predict prototype behavior is simpler and more reliable than in 1-g models for most cases due to the effects of self-weight stress states, as discussed above. For models which involve nonlinear material behavior, the stresses in the model will be equal to those in the corresponding prototype. If the same materials in a prototype are used for a model and if the model experiences the same stresses as the prototype, the strains will be the same at corresponding points within the model and prototype, and the patterns of deformation will be identical. Prototype time and time-dependent behavior can also be modeled in a centrifuge.

8. Three other important advantages/benefits of a centrifuge to the Corps of Engineers are: (a) prototype behaviors can be predicted for complicated problems (geometrically, constitutively, and numerically) for which numerical methods are not completely reliable or adequate, (b) numerical analysis solutions of engineering problems of performance and stability can be validated, improved, or developed based on equivalent prototype behavior, and (c) centrifuge tests can be beneficially used for parameter studies where material properties and behavior depend on both variation in boundary loads and conditions. Centrifuge testing allows the economical proof testing of designs, investigation of problem areas, and validation of numerical methods that have been prohibitively expensive to study with prototype or large scale model testing. Centrifuge testing allows evaluation and verification of analyses which have not been verified against significant truth data as well as the study of important behavior phenomena, including failure, that are impractical or not feasible to induce in prototype situations.

9. Full-scale destructive tests of structures (including geotechnical structures) are seldom performed because of prohibitive costs, extensive logistical difficulties, and safety considerations. The behavior of such structures is generally predicted by numerical modeling, but this technique is flawed without verification either by prototype behavior or by complementary physical model testing in a centrifuge or otherwise.

10. An important additional advantage which centrifuge modeling has over other physical modeling techniques (which can be seen from examination of similitude theory) is that time is scaled. Time for a diffusion process in a centrifuge model in flight proceeds at a rate n^2 times faster than normal

time where n is called the scaling ratio and is equal to the ratio of acceleration on the centrifuge to that of Earth gravity or the ratio of linear dimension in the prototype to the corresponding linear dimension in the model. Therefore, the effects of extended periods of time can be investigated by use of a centrifuge. Events which may require up to 30 years in normal time may be modeled in 1 day on a centrifuge operating at 100 g.

11. In a centrifuge, energy increases as the cube and force as the square of n ; at 100-g, 1-lb force on a model is equivalent to a 10,000-lb force on the prototype. The energy content of a gram of explosives at 100 g scales up to the energy of 1-million grams, or 1 ton of explosives; 1 gram of explosives at 300 g scales to the energy of 27-million grams, or 30 tons of explosives.

Modeling and Scaling

12. For a model test involving a nonlinear material, it is essential that the stresses in the model be roughly equal to those at homologous locations in the corresponding prototype. For example, a model dam 305 mm (1 ft) high experiences very different stresses from an actual dam with a height of 30.5 m (100 ft). The stress-strain and deformation patterns are quite different in the two situations. Self-weight of, and consequently, the stress fields for the 305-mm model can be increased to those in the 30.5-m prototype by increasing the gravity acting on the model 100 times by spinning the model in a centrifuge such that the centrifugal acceleration is 100 times that of Earth's gravity. The basic modeling principle is that at corresponding points in a small scale model the same stresses that exist in a prototype structure can be produced by increasing the weight of the model (by an artificial acceleration field) in the same ratio (n) that the scale of the model is decreased as compared with the prototype. For the same material in the model and prototype, the strains will be the same. For a given prototype structure to be modeled at a scale of n , the model experiment should be carried out at a centrifugal acceleration of $n \times g$.

13. For similitude to be satisfied, all length dimensions in a model, L_m , should be n times smaller than those in the prototype, L_p . Accelerations in the model, a_m , should be n times larger than those in the prototype, a_p .

14. Acceleration has units of L/t^2 where t = time. From dimensional analysis

$$L_m = \frac{1}{n} L_p \qquad (1)$$

and

$$a_m = n a_p \qquad (2)$$

$$a = \frac{L}{t^2} \qquad (3)$$

Therefore

$$\frac{L_m}{t_m^2} = n \frac{L_p}{t_p^2} \qquad (4)$$

and substituting from (1)

$$\frac{L_p}{n t_m^2} = n \frac{L_p}{t_p^2} \qquad (5)$$

simplifying yields

$$t_m^2 = \frac{t_p^2}{n^2} \qquad (6)$$

or

$$t_m = \frac{t_p}{n} \qquad (7)$$

15. Table 1 presents the scaling laws which are derived from dimensional analysis. For hydrodynamic modeling, additional scaling relationships

need to be considered and these are derived in Part II of this report. Similitude and scaling laws provide essential guidance concerning the planning and conduct of experiments. Due to conflicts in scaling laws for different phenomena such as time which affects rates of behavior, it is sometimes better to model only certain desired events or phenomena than the complete prototype behavior.

16. Difficulties arise in modeling dynamic events such as free vibration. In a model involving inertial effects, frequencies must be n times larger, particle velocities are the same, amplitude is n times larger, duration is n times shorter, and energy is n^3 times smaller than in the prototype. If diffusion, (e.g., consolidation and pore water pressure dissipation in soil or heat transfer in any solid) is important as well in the dynamic event, a problem arises, because, for diffusion events, model time is n^2 larger than the prototype time.

17. To deal with both inertia and diffusion events in a dynamic test where soil behavior is an important part of the test, the time scale for diffusion needs to be altered to match that of the inertial effects. One way to change the diffusion time scale is to adjust the material properties (e.g., coefficient of consolidation) in proportion to n which require a change in the permeability of the soil. A better method is to change the viscosity of the pore fluid which scales as the inverse of n; scaling of the fluid viscosity has been found to be effective for modeling both inertia and diffusion events in dynamic tests involving soil behavior (Schofield 1988).

18. Another problem in dynamic testing is the presence of rigid boundaries in the centrifuge model and the unwanted reflections of dynamic waves. Reflections can be significantly reduced by the use of absorptive material at rigid boundaries (Cheney et al. 1990). The use of a stacked-ring apparatus with low friction interfaces also inhibits reflections (Whitman et al. 1981). The best current method to control reflections is to use a large test container with or without absorptive material along the boundaries. Improved procedures for properly handling boundaries for different types of dynamic problems are needed.

19. An additional problem in dynamic testing is the effects of Coriolis acceleration in the plane of model rotation that can introduce undesirable stresses in the model mass and cause ejecta paths to be skewed. The Coriolis effect can be minimized by proper choice of the radius of the centrifuge arm,

rotational speed, and the direction of dynamic motion relative to the plane of centrifugal rotation. Dynamic excitation perpendicular to the plane of rotation is not affected by Coriolis acceleration.

20. Another major difficulty of modeling in the centrifuge is the replication of in situ soil conditions and the in situ loading history. Replication of in situ conditions is not a problem in applications such as verification of theories, parametric studies, understanding structural behavior, verification of numerical analyses, or study of soil response phenomena.

21. Modeling and interpretation problems arise if the stress-strain behavior of a material is strain-rate dependent. For true similitude, the time scales would need to be the same in the model and prototype. Problems can also be caused by the improper modeling of particle size. For geotechnical problems, the size of inclusions, such as piles, instruments, and probes in relation to both soil particle and model size, can cause distortion problems.

22. Potential problems can be controlled, and the results of centrifuge model tests can be validated. Any modeling technique, whether numerical or physical, has inherent uncertainties, and it is necessary to certify the validity of test results in some manner. Centrifuge scaling laws, boundary effects, particle size effects, inclusion effects, model size, strain rate, and flow behavior, to mention the most obvious, can be verified and investigated by the technique of modeling of models (Schofield 1988). Modeling of models is based on the concept that the prototype predictions and behavior from using centrifuge modeling techniques are independent of the scale used. As an example, the behavior of a 30.5 m high dam predicted by using a 305 mm high centrifuge model tested at 100-g centrifugal acceleration should be reasonably close to the results predicted by using a 610 mm high model tested at 50 g. By testing a number of models at different scales, the threshold or limits of centrifuge modeling for a particular prototype problem can be established concerning the ranges in which the above potential problems have little or no influence and where the test results are valid and comply with scaling laws.

23. Confidence can be gained in centrifuge results by showing that the test results agree reasonably well with predictions whose validity has been established by other means. The final confirmation of centrifuge modeling can

only come from showing that the test results are reasonably close to field observations.

24. The potential problems which have been discussed emphasize the difficulties in modeling a specific prototype problem with true similitude. However, every test can be interpreted as representing some aspect of a full-scale situation. By the use of scaling laws, proper interpretation, and modeling of models, prototype conditions within the range of practical interest can be studied.

Model Size and Acceleration

25. There are several criteria that govern the choice of model size and acceleration when designing a centrifuge model testing program. These criteria include: (a) the purpose of the experiments, (b) the dimensions and mass of the prototype that is to be studied, (c) the size and acceleration requirements for model validation test series, (d) the resolution requirements for measuring small volume phenomena, (e) the space required on the centrifuge platform or in the model container for necessary test equipment, (f) the size of measurement instrumentation and inclusions compared with the model and its materials and components, and most importantly, (g) the *model dimension* limitations in order to minimize the boundary influences from the platform and model container side walls as they effect the results for the specific purpose test. One method for sizing a model and limiting the boundary effects is to use the boundary extents dictated by a numerical model. For example, the numerical model for a dam may require that at least 61 m of the foundation thickness be used in order to limit the stress effects to less than 10 percent; therefore, the centrifuge model for the dam should have at least a modeled 61-m-thick foundation.

26. Most often, modeling programs are designed to take full advantage of the size and/or acceleration capacity of a given centrifuge. A centrifuge test of a large model at full acceleration might be considered for modeling the stress conditions of a large and massive prototype. However, a large model might be tested at a relatively low acceleration so that scale effects are clearly avoided, the small volume phenomena and mechanisms can be monitored, and all measurements can be made with the least disturbance from the measurement instrumentation. For model validation studies using the

modeling of models technique, a small model tested at full acceleration would likely be used for one test configuration extreme; whereas, a large model tested at low acceleration would be the other extreme.

PART II: CENTRIFUGE APPLICATIONS IN COASTAL ENGINEERING RESEARCH

Introduction

27. Coastal engineering involves many different aspects of the natural processes occurring in the nearshore region. Activities can range from trying to understand the complex physical interactions, through rational design of protective structures and harbors, to prediction of impacts stemming from man's utilization of the coastal region. Most problems in the coastal realm involve the hydrodynamic interaction of water with sediment or structures, which act as boundaries to the fluid.

28. Physical models at reduced scale and 1 g have been used successfully for many years to study and solve a multitude of coastal problems. Although advances in theoretical understanding of the complex coastal regime and subsequent numerical simulation of the processes have become more common in recent years, there are still instances when physical models (or numerical models calibrated using physical model measurements) provide the only means of arriving at a reliable solution to specific complex flow regimes. Examples include wave penetration into harbor complexes, wave and current interaction at the mouth of entrance channels, and wave generation and propagation of explosion generated waves.

29. In many instances, physical model scaling relationships for the hydrodynamic processes occurring in the coastal region have been theoretically established and exhaustively proved by successful scale modeling of prototype-scale events. Some problems, such as sediment transport, have frustrated researchers attempting to establish scaling guidance based on theoretical considerations. Consequently, investigators have attempted to develop empirical scaling criteria based on observed prototype and model response of some gross feature of the process. In the case of sediment transport processes, profile development and scour hole formation are just two of the possible features the experimenter may wish to reproduce in the model. In other cases, prototype data are rare or nonexistent, forcing the researcher to conduct an experimental scale series where the same experiment is reproduced at different scales to observe the scale effects. If empirical scaling relationships can be developed based on the results of the scale series and the scaling guidance

is sufficiently general over the range of expected usage, the model results can be projected to prototype scale with increased confidence.

Potential Centrifuge Applications

30. Past applications of physical modeling to coastal problems have been contained by the reality that gravitational acceleration is the same in the model as in the prototype. Although this has not particularly limited the usefulness of physical hydrodynamic models for coastal engineering, the prospect of operating a hydrodynamic physical model under increased gravitational loading offers the researcher an additional model parameter that can be varied to properly scale the prototype situation.

31. In the coastal regime, several potential research applications are candidates for centrifuge testing as follows:

a. Explosion generated waves. Wave generation and propagation associated with high yield explosions can be scaled for centrifuge testing. This would provide data on wave characteristics in shallow water for use in development and refinement of theoretical and numerical models at a greatly reduced cost over conventional scale model tests. Explosion wave effects on specific harbor or port facilities could be economically examined.

b. Marine foundations. Geotechnical failure of foundations beneath coastal structures or offshore platforms can be investigated. Failure is possible when cyclic wave loading of the structure creates conditions favorable for liquefaction or strength degradation of the underlying foundation material.

c. Tsunami runup. Tectonically generated long period waves (termed *Tsunamis*) can devastate coastal regions. Numerical solutions provide reasonably accurate estimates of tsunami runup when bathymetry is relatively simple; however, the numerical simulations are not as reliable when applied to complex bathymetric configurations. The centrifuge offers the possibility of physically modeling these long waves and measuring the associated runup in complex situations. Results will aid in refining present numerical techniques.

Undoubtedly, other centrifuge applications for coastal engineering will become evident.

32. One important aspect of coastal engineering that will require research and may not easily lend itself to centrifuge testing is sediment transport. Sediment particle size may have to be scaled to a size where interactive particle forces do not model the prototype situation. In 1-g model tests, a solution to this problem has been to use lightweight materials as the

model sediment. Increased gravitation in the centrifuge may counteract this solution by making it more difficult for the modeled flow to move the sediment particles. However, the flow forces also increase in the centrifuge. Centrifuge tests of erosion of soils from overtopping of dams and embankments indicate that particle size may not be a major limiting factor (Townsend et al. 1979, Goodings 1984, and Ko et al. 1984).

Hydrodynamic Scaling Relationships

33. Complete similitude in hydrodynamics, in the strictest definition, requires geometric, kinematic, and dynamic correspondence between the prototype and the model at all times at all locations in the flow. Geometric similarity exists between two systems if the ratios of all corresponding linear dimensions are equal. This relationship is independent of motion of any kind, and in coastal engineering usually refers to solid boundaries and bottom configuration. Kinematic similarity is similarity of motion. In geometrically similar systems, kinematic similarity is obtained when the prototype-to-model ratio of the velocity components at a point is equal for all points in the fluid. Dynamic similarity between two geometrically and kinematically similar systems requires that the ratios of all forces in the two systems be the same. The forces which can potentially affect fluid models are inertial (mass reaction to the active forces), and the active forces of pressure, gravitation viscous force, surface tension, and elastic compression.

34. In reality, complete similarity can never be met except for the special case when the prototype and model are the same size. Fortunately, many flow problems in hydraulic and coastal engineering can tolerate a relaxation of the strict similitude requirements because the inertial response in the flow regime is dominated by only one of the five active forces. In these situations a geometrically reduced model can be constructed and operated such that dynamic similarity is maintained for the dominant active force with the knowledge that those forces which are incorrectly scaled will have only minor influence on the observed model behavior. Although past experience has helped to reinforce this relaxation of the similitude requirements for many flow cases, the model designer has the responsibility to carefully examine the forces inherent in any flow situation which is physically modeled to ensure that forces assumed to be minor in influence are indeed negligible.

Scaling notation

35. Scaling relationships are typically expressed as dimensionless ratios of the prototype parameter to the corresponding model parameter. The notation for scale ratios used herein is defined as

$$N_X = \frac{X_p}{X_m} \tag{8}$$

where N_X is the ratio of the subscripted parameter in the prototype (X_p) to the value of the parameter in the model (X_m).

Froude scale

36. The overwhelming percentage of flow problems in coastal engineering involves surface wave motion where gravity is the predominant restoring force. Hence, the appropriate similitude calls for maintaining the ratio of inertial forces to gravity force between prototype and model, and neglecting the effects of the other forces. This ratio of inertial forces to gravity force is represented by the Froude Number

$$F_* = \frac{V}{\sqrt{gL}} \tag{9}$$

where

V = flow velocity

g = gravitational acceleration

L = characteristic length

Maintaining the ratio of inertial to gravitational forces between prototype and model equates to the requirement that the Froude Number be the same in prototype and model, or

$$\frac{V_p}{\sqrt{g_p L_p}} = \frac{V_m}{\sqrt{g_m L_m}} \tag{10}$$

where the subscripts p and m refer to prototype and model, respectively. Applying the definition for scale ratios given by Equation 8 such that the velocity scale ratio in $N_v = V_p/V_m$ and rearranging Equation 10:

$$N_v = \sqrt{N_g N_L} \tag{11}$$

where

N_g = gravity scale ratio N_p/N_m

N_L = length scale ratio L_p/L_m

37. Time scale is determined by recognizing that velocity is length divided by time, i.e., $V = L/T$, giving the relationship $N_v = N_L/N_T$, which when substituted into Equation 11 gives

$$N_T = \sqrt{\frac{N_L}{N_g}} \tag{12}$$

Equations 11 and 12 are equivalent forms of the scaling relationship known as the Froude Law. In normal practice gravity is assumed to be the same in the model and prototype so that $N_g = 1$, but this will not be true in centrifuge applications.

Reynolds scale

38. Situations where viscous forces dominate flow occur more frequently in hydraulic engineering applications than in those of coastal engineering. An example is steady flow in a conduit where gravity forces cancel and there is no free surface to introduce surface tension effects. Viscosity plays a role in a few coastal engineering applications, such as viscous wave damping over long distances, boundary layer effects on sediment motion, and flow past solid bodies. Therefore, it is necessary to be aware of the pertinent scaling ratios required for maintaining flow similarity when viscous forces are predominant.

39. The ratio of inertia forces to viscous forces is given by the Reynolds Number

$$R_* = \frac{LV}{\nu} \tag{13}$$

where ν is the fluid dynamic viscosity. Maintaining the same value of Reynolds Number in both prototype and model, i.e.,

$$\frac{L_p V_p}{\nu_p} = \frac{L_m V_m}{\nu_m} \qquad (14)$$

assures the correct relationship between inertia and viscous forces. Rearranging Equation 14 and invoking the scale definition of Equation 8 yields the scaling relationship between inertia and viscous forces known as the Reynolds Law.

$$N_\nu = N_L N_V \qquad (15)$$

Replacing the velocity scale ratio, N_V, with N_L/N_T gives an alternate form of the Reynolds Law as

$$N_L = \sqrt{N_\nu N_T} \qquad (16)$$

In small models scaled using the Froude Law, potential viscous scaling effects can be evaluated in terms of the Reynolds Law. Often, roughness elements are used in the model to artificially induce increased turbulence levels so that Reynolds similitude is more closely met.

Weber scale

40. Surface tension effects are rarely significant in coastal engineering modeling except when the size of the model has to be made so small that surface waves fall within the range of capillary waves. The ratio of inertial forces to surface tension forces is given by the Weber Number

$$W* = \frac{V}{\sqrt{\frac{\sigma}{\rho L}}} \qquad (17)$$

where

σ = surface tension per unit length

ρ = fluid density

Appropriate similitude is obtained when the Weber Number is held constant between prototype and model, i.e.,

$$\frac{V_p}{\sqrt{\frac{\sigma_p}{\rho_p L_p}}} = \frac{V_m}{\sqrt{\frac{\sigma_m}{\rho_m L_m}}} \tag{18}$$

Rearranging Equation 18, invoking the scale ratio definition of Equation 8, and replacing N_V with N_L/N_T gives the scaling relationship known as the Weber Law, i.e.,

$$N_T^2 N_\sigma = N_L^3 N_\rho \tag{19}$$

At the small model sizes anticipated for centrifuge testing, it will be necessary to evaluate potential surface tension effects in wave motions.

Potential surface tension effects

41. Surface tension effects in gravity waves can be evaluated via the linear wave theory dispersion relation. The dispersion relation uniquely relates the wave length and the wave period for a given water depth. The dispersion relation is given as:

$$\omega^2 = \left(gk + \frac{\sigma k^3}{\rho}\right) \tanh(kh) \tag{20}$$

or

$$\omega^2 = \underbrace{gk \tanh(kh)}_{\textit{gravity term}} + \underbrace{\frac{\sigma k^3}{\rho} \tanh(kh)}_{\textit{surface tension term}} \tag{21}$$

where

ω = $2\pi/T$, where T is wave period

g = gravity

k = $2\pi/L$, where L is wave length

ρ = fluid density

σ = surface tension coefficient

h = water depth

42. Equation 21 can be used to determine the wave length at which the gravity term is M times more influential than the surface tension term, i.e.,

$$gk \tanh(kh) = (M) \frac{\sigma k^3}{\rho} \tanh(kh) \tag{22}$$

Rearranging Equation 22 and replacing k with $2\pi/L*$, where L* denotes the specific wave length in question, gives

$$L_* = 2\pi \sqrt{\frac{M\sigma}{\rho g}} \tag{23}$$

Typical fluid properties (English units) are $\sigma = 0.074$ N-m/m^2 , $\rho = 1025.37$ kg/m^3 , and $g = 9.807$ m/sec^2 . Substitution into Equation 23 gives

$$L_*(ft) = 17.03835(mm)\sqrt{M} \tag{24}$$

which can be used to evaluate surface tension impacts under normal gravity. For example, the wave length where gravity forces are 10 times more important than surface tension forces is found when M is 10, i.e., $L_* = 53.9497$ mm .

43. A scaling relationship for the relative importance, M , of surface tension can be developed by maintaining the same relationship given Equation 23 between prototype and model, or,

$$\frac{(L_*)_p}{(L_*)_m} = \frac{\left(2\pi\sqrt{\frac{M\sigma}{\rho g}}\right)_p}{\left(2\pi\sqrt{\frac{M\sigma}{\rho g}}\right)_m} \tag{25}$$

which yields in terms of scale ratios...

$$N_{L_*} = \sqrt{\frac{N_M N_\sigma}{N_\rho N_g}} \tag{26}$$

Rearranging Equation 26, and noting N_{L*} must be the same scale ratio as N_L gives

$$N_M = \frac{N_\rho N_g N_L^2}{N_\sigma} \tag{27}$$

44. Preserving the relative contributions of gravity and surface tension between model and prototype requires $N_M = 1$. For the same fluid in both prototype and model, i.e., $N_\rho = N_\sigma = 1$, Equation 27 reduces to

$$N_L = \frac{1}{\sqrt{N_g}} \tag{28}$$

45. Scaled hydrodynamic wave models that do not meet the criterion of $N_M = 1$ must be checked using Equation 23 to assure that the gravity contribution far outweighs the surface tension contribution for the lengths of the model waves. At a minimum, the gravity term should be 10 times ($M = 10$) greater than the surface tension term.

Explosion Generated Wave Studies

46. Much progress has been made in predicting the wave effects stemming from large yield explosions in water. Since 1980, theories and numerical simulation techniques have been extended to the point that much of the wave propagation problem has been adequately described. Two aspects which have yet to be resolved are wave generation, expressed in terms of the explosive gas bubble growth and collapse, and nonlinear propagation of explosion generated waves into harbors or embayments.

Explosion wave scaling

47. Explosion cavity formation in water has many of the characteristics of crater formation in soil. However, in water, the fluid is considered completely devoid of shear strength, and the only restoring force is gravity. Experiments conducted at reduced scale have resorted to the Froude relationship given by Equation 12 with the gravity scale ratio set to one. The major drawback to the study of explosion bubble dynamics at normal gravity is that

the atmospheric pressure must be reduced accordingly so that bubble expansion is correctly simulated. Generally, this poses almost insurmountable problems.

48. Pioneering efforts by Schmidt and Housen (1987) demonstrated that a high-speed centrifuge could be employed to study bubble formation and collapse at greatly reduced scale without sacrificing correct similitude. They presented the scaling requirements for both reduced atmospheric pressure tests and for increased gravity tests. These scaling requirements are given in Table 2 in terms of scaling ratios (defined in Equation 8).

49. In Table 2, the last column presents the special case of increased gravity scaling when the centrifuge g-loading is selected to be equal to the length scale ratio. It should also be noted that the relationships in Table 2 have been derived under the assumption that the fluid (water) is the same in the model as in the prototype, i.e., $N_{\rho} = 1$.

50. Besides the problem of reducing the atmospheric pressures in conventionally scaled tests under normal gravity, questions arise concerning the proper scaling of the energy. Explosive energy creating bubble cavities is proportional to the volume of the formed bubble. Therefore, it would be desirable for the energy to scale as the cube of the length scale. As can be seen in Table 2, reduced pressure scaling under normal gravity does not give this relationship. This lead Schmidt and Housen (1987) to suggest that the centrifuge g-loading be made the same as the length scale ratio ($N_L = n$). This selection resolves the atmospheric problem as well as the energy problem, thus assuring correct bubble formation and collapse in the centrifuge model. Therefore, the proper scaling relationships for bubble dynamics are given in the rightmost column of Table 2.

Applications

51. Testing and measurement of explosion crater formation in shallow water, where the bottom influences the shape of the explosion bubble, are the only feasible ways to systematically attack the shallow water explosion wave generation problem. A large centrifuge with capability of approximately 300-g centrifugal acceleration would allow models up to scales of 300 to 1. Because the energy scales as the cube of the length scale, model charges as small as 1 gram would be equivalent to prototype yields of 27,000 kg (≈ 59,400 lb) at 300-g centrifugal acceleration.

52. Because correct reproduction of explosion bubble dynamics restricts the length scale to being equal to the g-loading, limitations are imposed on

the atmospheric pressure must be reduced accordingly so that bubble expansion is correctly simulated. Generally, this poses almost insurmountable problems.

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52. Because correct reproduction of explosion bubble dynamics restricts the length scale to being equal to the g-loading, limitations are imposed on

because relatively larger yields can be modeled at less risk to the container. A capability of at least 300 g is warranted. Table 3 summarizes these requirements.

Experimental considerations

57. Design of centrifuge tests simulating explosion wave generation and propagation needs to consider possible surface tension effects, viscous effects, and measurement techniques. The previous section on scaling presented equations for examining surface tension effects in Froude models and calculating wave lengths where these effects become a concern.

58. Viscous effects might become important in models where explosion waves are causing runup on shore facilities. Wave energy dissipation may not be the same in the model as in the prototype, and appropriate parameters relating to frictional dissipation of waves must be examined prior to interpreting results.

59. Schmidt and Housen (1987) used very high speed filming of explosions in a centrifuge to quantify bubble cavity growth. At the time scale of bubble dynamics, high speed photography may be the best technology that can permit these measurements. Runup of explosion waves will require some means of registering the maximum runup. A possible solution would be electronic sensors built into the runup slope.

Advantages to centrifuge testing

60. As mentioned previously, the centrifuge offers the only viable means of studying and quantifying explosion wave bubble growth and collapse outside of full-scale testing. Centrifuge testing would be significantly less expensive than prototype-scale testing of moderate yield TNT shots, and the scaling relationships indicate that the centrifuge results would be more representative of prototype high yield explosions. The prospect of obtaining many data sets of different conditions would add greater confidence to empirical and theoretical relationships between yield and explosion bubble cavities resulting in more accurate numerical prediction programs for use in strategic planning and operations.

Marine Foundation Studies

61. Marine foundations pose a special problem for geotechnical engineers because the underlying bed material is normally saturated and can be

subjected to cyclic loading by heavy wave action on the structure being supported by the bed material. Potential liquefaction of the foundation or strength degradation through cyclic loading are two possible adverse effects that can be examined with centrifuge testing.

62. The geotechnical aspects of centrifuge modeling of marine foundations will be the same as discussed in other parts of this report; therefore, scaling will not be discussed in detail. Scaling is performed so that the bed material properties exhibit the same characteristics as prototype scale. Model length scales can then be determined so that the modeled regime fits into the space constraints of the centrifuge platform.

63. After determination of length scale for the proposed marine foundation model, the prototype hydrodynamic loading must be idealized so that the cyclic water motions can be reproduced in the centrifuge. The Froude scaling criterion of Equation 12 is appropriate. Most likely, for the scale of wavelengths that might be considered for centrifuge testing of marine foundations, surface tension effects will not be important because the emphasis is on the soil response to hydrodynamic motion at a given frequency rather than the precise amplitude of the driving frequency. If it is necessary to generate specific irregular wave loading conditions, special consideration must be given to wave generation techniques (see the later section on "Considerations for Hydrodynamic Models").

Applications

64. Previous centrifuge testing of marine foundations has been conducted at Cambridge University, England, in studies of offshore oil drilling platform foundations in relatively deep water (46-78 m) as reported by Schofield (1988). Soil conditions in the Bass Strait, Australia, were simulated in the centrifuge to provide rapid and cost-effective design solutions to the unique soil conditions at the site. More recently, Cambridge University tested foundation performance of vertical seawalls subjected to earthquake loading for application in Japan.

65. The study of various types of soils underlying coastal rubble-mound structures, such as breakwaters and jetties, is also possible. Present foundation design could be improved by looking at the aspects of soil compaction, loading and unloading of the soil during tidal cycles, and nesting of armor units on newly built or recently rehabilitated structures.

Model size and acceleration

66. Marine foundation experiments have essentially the same centrifuge size and acceleration requirements as geotechnical studies of building foundations. The largest offshore marine structure will have maximum dimensions of approximately 200 m × 200 m. This is well within the footprint required to conduct typical land-based foundation studies.

Advantages to centrifuge testing

67. The same advantages the centrifuge offers for most geotechnical foundation studies apply to testing of marine foundations. These advantages are detailed in other parts of this report and will not be further discussed here other than to restate that testing is rapid, economical, and often represents the only practical alternative.

Tsunami Runup Studies

68. Tsunami waves are water waves created by sudden tectonic movements of the Earth's crust, usually associated with earthquakes. When an earthquake occurs somewhere in an ocean basin and a displacement of the seafloor results, the change in hydrodynamic boundary conditions generates a wave train having low amplitude and very long periods that propagates radially outward from the source of the disturbance. Typical Tsunami waves have periods between 5 and 30 min, and wave heights less than 300 mm. Tsunamis can travel undetected in deeper ocean waters, but they can render incredible damage when they impact the shoreline. As the tsunami moves into progressively shallower water, the wavelengths become shorter and conservation of wave energy results in very high wave heights. Tsunami damage to port and harbor facilities has been well documented, and tsunami warning systems are in place throughout the Pacific Rim.

69. Because of the long wave periods associated with tsunami waves, conventional physical models cannot be built large enough to properly simulate tsunami transformation in coastal waters. Fortunately, theoretical and numerical developments have largely filled this void due, in large part, to the fact that tsunami waves essentially satisfy the long wave equation and are mathematically tractable. However, these highly developed mathematical models still have difficulties estimating tsunami wave runup over complex bathymetry

or within complex harbor configurations. This is partly because little validating data exist for comparison with numerical results.

Centrifuge scaling of tsunami waves

70. Tsunami waves in the coastal zone can be effectively treated as gravity waves, hence, the appropriate scaling relationship is the Froude criterion given by Equation 12. Replacing the gravity scale ratio in Equation 12 with the definition $N_g = 1/n$, where n is the g-loading of the centrifuge, gives the time scale ratio as

$$N_T = \sqrt{n}\sqrt{N_L} \quad (29)$$

71. The advantage gained by conducting the experiment in a centrifuge is that the time scale factor, N_T, is increased by $\sqrt{n}$ over what it would be under conventional physical model testing. This advantage is offset somewhat by the requirement that the model must be quite small to fit into the centrifuge test container. However, model costs drop dramatically as the length scale ratio increases.

Model size and acceleration

72. Centrifuge size requirements for successful simulation of tsunami runup in complex regions are governed primarily by the length scale required to fit the modeled region onto the centrifuge platform. Therefore, platform size is more important than acceleration for this case. Acceleration comes into account when determining required wave periods in the model. For example, a coastal region of 1 km at a length-scale reduction of 1:1000 would require a centrifuge platform dimension of 1 m. A tsunami with a wave period of 600 sec would have a period of 1.6 sec under 150 g and a period of 1.1 sec at 300 g. Platform dimensions less than 1 m × 1 m will have little utility for tsunami modeling. These requirements are summarized in Table 3.

Applications

73. Just as explosion generated waves can impact coastal facilities, tsunami waves have the potential of doing even more damage. Numerical models could be refined based on measurements of tsunami runup in a centrifuge. Refinement is most needed in making runup estimates over complex bathymetry or in harbor facilities, and these situations may be well suited to centrifuge testing. Other more fundamental studies of long-period infragravity waves may also be candidates for centrifuge studies because long wave generation might

be less of a problem in a centrifuge. Study will need to be made on potential generation techniques for long-period wave motions in a centrifuge. The generation of tsunami waves may be better accomplished using some mechanical means other than direct simulation of a tectonic event.

Special Hydrodynamic Cases

74. Besides the specific applications for centrifuge testing discussed earlier in this part, there are probably several other applications that either have been overlooked or which have yet to be conceived. Those special hydrodynamic cases that appear suitable for centrifuge testing will probably be cases that require more than inertial forces and one active force to be in similitude between prototype and model.

Similitude of inertial, gravity, and viscous forces

75. The special case arising from the necessity of exactly preserving the effects of both gravity and viscous forces on the resulting inertial reaction can only be satisfied at full scale under normal 1-g gravitational loading. However, centrifuge testing allows a limited range of reduced scales where these requirements can be met. This range can be defined in terms of scale ratios by requiring Froude and Reynolds scaling criteria be met simultaneously.

76. The Froude and Reynolds criteria were derived earlier and were expressed in terms of scale ratios in Equations 12 and 16, respectively. Rearranging Equation 16 as

$$N_T = \frac{N_L^2}{N_\mu} \tag{30}$$

and substituting this result for N_T in the Froude criterion (Equation 12) gives

$$N_g N_L^3 = N_\mu^2 \tag{31}$$

77. Equation 31 can be used to properly scale hydrodynamic models in the centrifuge when both Froude and Reynolds criteria must be met. An idea of the range of scale when the same fluid as in the prototype is used in the model is obtained by setting $N_\mu = 1$, and remembering that the gravity scale is defined as $N_g = 1/n$ where n is the g-loading factor of the centrifuge. This results in the special case of

$$N_L = n^{1/3} \tag{32}$$

78. Thus, it is seen that a centrifuge with acceleration capability up to 350 g ($n = 350$) can accommodate hydrodynamic models obeying both Froude and Reynolds criteria up to scale ratios of $N_L = 7.03$ when the fluid is the same as in the prototype.

Similitude of inertial,
gravity, and surface tension forces

79. Earlier, a scaling relationship was derived for the relative importance of surface tension in gravity waves (Equation 27). Requiring $N_M = 1$ in Equation 27 yields the scaling relationship for simultaneously meeting the Froude and Weber criteria, i.e.,

$$N_L = \sqrt{\frac{N_\sigma}{N_\rho N_g}} \tag{33}$$

This result could also be obtained by equating Equations 12 and 19.

80. For the special case of same model and prototype fluid ($N_\sigma = N_\rho = 1$), and replacing N_g with $1/n$, the derived length scale becomes

$$N_L = \sqrt{n} \tag{34}$$

Therefore, the maximum length scale ratio at which gravity and surface tension can be held in similitude with the prototype is approximately $N_L = 19$ for a g-loading of $n = 350$.

81. Although the above two special cases do not pertain to immediate needs in coastal engineering, it is instructive to develop the possibilities in order to broaden the potential uses of a large high-speed centrifuge.

Considerations for Hydrodynamic Models

82. Centrifuge testing of hydrodynamic models poses several interesting aspects deserving special consideration. These are discussed briefly.

Water surface curvature

83. The normal scale of water motions of interest in coastal engineering is sufficiently small that the Earth's radial gravitational field can be considered to act only in the vertical direction over the extent of the flow. In other words, it is usually not necessary to consider the Earth's curvature in hydrodynamic problems. On the other hand, the radial gravitation force field induced by a centrifuge has a distinct curvature over the extent of the testing platform. This will cause a similar curvature of the hydrodynamic fluid's free surface as g-loading occurs. Fortunately, the curvature is strictly a function of centrifuge geometry, and is independent of g, provided $g \gg 1$. However, hydrodynamic models will need to be corrected for this curvature to simulate prototype conditions realistically.

84. The error that would result from not curving the base of a model test tank can be calculated as follows. Figure 1 shows a planview sketch of a rectangular basin of length, B, containing a fluid with unaccelerated free surface a distance, R, from the centrifuge pivotal point. As the centrifuge creates the radial acceleration on the fluid, the free surface deflects into the form of an arc. Conservation of mass dictates that the volume of fluid setdown displaced from the still fluid level be equal to the volume of fluid setup observed at the basin edges.

85. Starting with the two given parameters B and R, geometric considerations and conservation of mass yield three equations in three unknowns (C, r, and θ):

$$C = \frac{\theta r^2}{B} - R \tag{35}$$

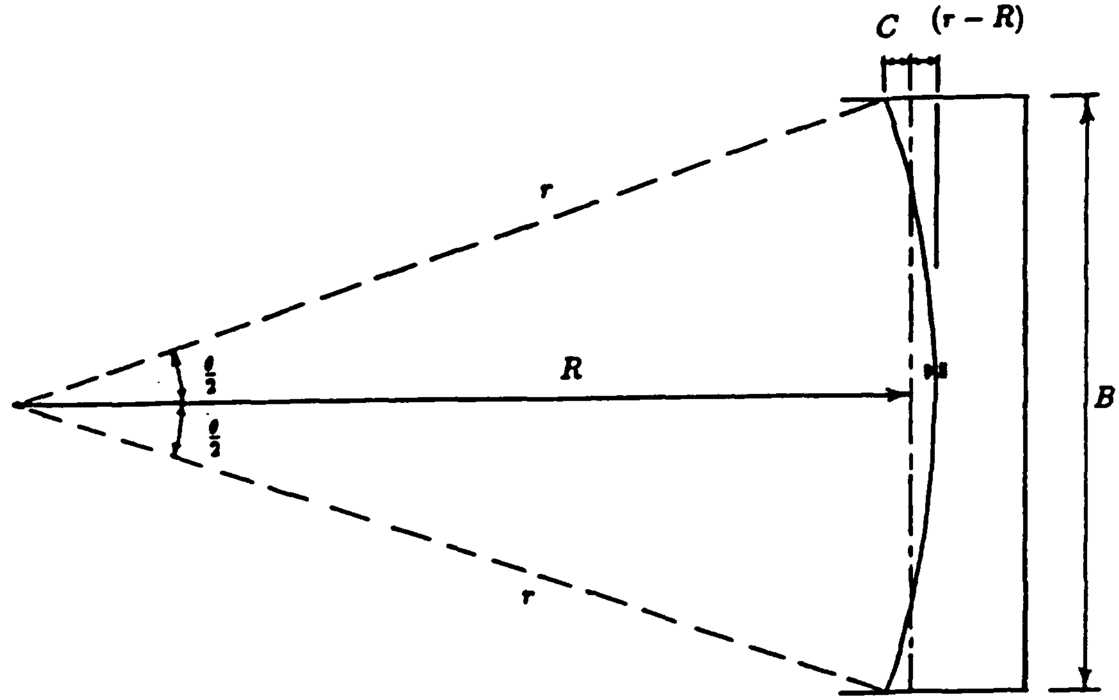

Figure 1: Planview of hydrodynamic model in centrifuge

$$r^2 = \left(\frac{B}{2}\right)^2 - (R - C)^2 \tag{36}$$

$$\sin\left(\frac{\theta}{2}\right) = \frac{B}{2r} \tag{37}$$

86. Generally, these three equations require an iterative solution; however, the usual geometry of a large centrifuge makes the small angle assumption, $\sin \phi = \phi$, a reasonable approximation. Making this assumption and substituting Equation 37 into Equation 35 produce the result which

$$C = r - R \tag{38}$$

means the maximum setdown is equal to the maximum setup at the vertical boundary. The deflection distance is found from Equation 36 to be

$$C = \frac{B^2}{16R} \tag{39}$$

87. For a centrifuge with nominal dimensions of $B = 1.5$ m and $R = 6.0$ m , the setdown is about 2.3 cm, and the total curvature is twice that amount, or about 4.7 cm. Clearly, it will be necessary to accurately incorporate the same curvature into the bathymetry being represented in the model because this amount of curvature could easily be greater than the wave heights generated in the model. If the model test tank is oriented with its length parallel to the centrifuge axis, then there is much less curvature along the tank length; these matters all require care in choice of model test arrangements.

Wave maker considerations

88. Several of the centrifuge applications mentioned previously could involve the need to mechanically generate waves in the centrifuge test container. This would require installation of some type of wave board to disturb the wave surface along with a controlling mechanism and an appropriate supply of power. Because a wave maker disturbs the water, it must provide enough energy to momentarily overcome the gravitational restoring force. In a centrifuge, the gravitational force is increased; therefore, the wave maker will need a commensurate increase in power to accomplish the task.

89. Linear wave theory for specific types of wave generators is well established and can be used to determine the necessary wave board stroke required to generate waves of specific height and period in the centrifuge. An estimate of power requirements for wave generation in the centrifuge can be determined in terms of scale ratios using linear wave theory. Wave power is given as

$$P = EC_g \tag{40}$$

where

$$E = \frac{\rho g}{8} H^2 \text{ , wave energy, and}$$

$$C_g = \frac{L}{T} \frac{1}{2} \left(\frac{\sinh(2kh) + 2kh}{\sinh(2kh)} \right), \text{ group velocity,}$$

or

$$P = \frac{\rho g H^2 L}{16T} \left(\frac{\sinh (2kh) + 2kh}{\sinh (2kh)} \right) \tag{41}$$

Hyperbolic term

90. The scale ratio of power is found from Equation 41 in terms of scale ratios as

$$N_P = \frac{N_\rho N_g N_H{}^2 N_L}{N_T} \tag{42}$$

Note that the prototype-to-model scale ratio of the hyperbolic term is unity because kh is already dimensionless.

91. Equation 42 can be further reduced by substituting the Froude relationship (Equation 12) for N_T , and recognizing that N_H is simply the length scale, N_L . This results in

$$N_P = N_\rho N_g{}^{3/2} N_L{}^{5/2} \tag{43}$$

For the more specific case with the same prototype and model fluid ($N_\rho = 1$), and substitution of $N_g = 1/n$, Equation 43 becomes

$$N_P = \frac{N_L{}^{5/2}}{n^{3/2}} \tag{44}$$

92. Thus, the necessary power requirements for wave generation in a centrifuge increases as the 3/2 power of the centrifuge g-loading (n). This can become very significant near loading of 300 g and, consequently, must be evaluated when designing potential wave maker applications.

PART III: CENTRIFUGE APPLICATIONS IN COLD REGIONS RESEARCH

Introduction

93. Compared with conventional geotechnical centrifuge modeling, the use of the centrifuge for frozen ground and ice engineering problems is in its infancy, and many modeling issues remain to be clarified before cold regions centrifuge experiments become routine. Any frozen ground centrifuge modeling exercise that is conducted in the near future will of necessity include basic research into the requirements for achieving similarity between model and prototype. In any engineering discipline, the capability to generate valid prototype-level data from small scale models is highly desirable. Because many frozen ground and ice engineering problems involve self-weight dependent response mechanisms, the centrifuge should be investigated as a modeling technique for such problems. As indicated by the body of documented work to date, several researchers have initiated centrifuge modeling studies in this area. A centrifuge with cold temperature capabilities would provide an opportunity for the Corps of Engineers to be a leader in this developing field.

94. Many problems that are encountered in frozen ground and cold regions geotechnical engineering would be better understood if the testing of small scale models provided valid and relatively inexpensive data from which prototype behavior could be inferred. The advantages of having a small scale modeling capability for frozen soil applications are the same as for many engineering applications; i.e., model testing programs can be designed to complement full or large scale tests, or, when full scale testing is not possible or economically feasible, model tests can be conducted to obtain experimental data of the structural response in lieu of full scale measurements. The specific advantage of centrifuge modeling as a small scale modeling technique is that the weight stresses of a structure are simulated rather than neglected as is common for other forms of small scale modeling. Centrifuge testing would be an appreciable advance for cold regions geomechanics if engineers could take advantage of such a tool for the study of frozen ground structures.

95. For small scale testing in general, the scaling laws for centrifuge modeling do not always allow the geotechnical experimenter to achieve reasonable similarity between model and prototype. Because of the viscous and

cohesive nature of frozen soil and because of the complexities of phase change processes in frozen soil structures, the limitations appear to be greater. Since centrifuge modeling for frozen ground structures is not an advanced research area, this part considers many of the potential limitations of small scale frozen soil modeling and the use of the centrifuge for this modeling.

Potential Centrifuge Applications

96. Studies regarding frozen ground application should begin with the basic research and experimental technique development that would be expected in any new physical modeling study. Experiments for a given application would be designed to investigate and establish (a) the need for the centrifuge as a modeling tool for the application, (b) the dominating behavior mechanisms and the associated scale factors, (c) the limitations associated with any scale effects or time scale conflicts, and (d) the technical problems concerning construction of the model with the prototype material. Such an investigation would provide the greatest detail to date regarding the similarity of model and prototype for frozen ground studies.

97. In the context of the technical issues and potential modeling limitations described in the following sections, several applications can be mentioned. These are as follows with both frozen ground and ice engineering problems included.

a. General studies of the mechanics of frozen ground and freeze-thaw processes: mechanisms of soil freezing and thawing processes; ground ice lense formation; fluid and heat transfer mechanics; short term deformation; and failure mechanisms in frozen ground structures.

b. Engineered facilities and structures: stability and short term deformability of foundations on continuous or discontinuous permafrost; stability and short term creep of tunnels in permafrost; stability and deformability of, and liquid flow through, frozen and partially frozen earth embankments and earth and tailings dams; frost heave processes and mechanisms under pavements and foundation structures; frost heave processes and mechanisms in soil structures; mechanical and thermal interactions between surface and buried structures and ground; iceberg scour of sea floor with buried pipelines; dynamic response of frozen ground and geotechnical structures; ice-structure interaction; ice rubble formation during pressure ridge building process; ice pileup and rideup along a coastline.

c. Artificial freezing process design: process selection; freezing front, heat transfer, and frost heave observations during artificial freezing; creep, deformation, and fracturing observations.

d. Environmental studies: contaminant flow through freezing, frozen, and thawing ground; damage of clay seals and caps due to freezing and thawing processes; damage of frozen clay seals and caps due to subsidence and other landfill deformations.

e. Planetary expeditions: similarity modeling of construction processes and constructed facilities on and in extraterrestrial permafrost for preexpedition design.

Cold Regions Modeling

98. In the physical modeling context, cold regions geotechnical problems can be distinguished according to the extent of the frozen soil in a model. Models whose entire volume is comprised of frozen soil (i.e., soil, pore ice, and unfrozen pore water) can be considered to be distinct from models with zones of both frozen and unfrozen soil, just as they are distinct from models comprised solely of unfrozen soil. These distinctions are made because if the soil of a model test is not frozen throughout the volume of the model, then the similarity of effective stresses and response mechanisms between the model and prototype in the unfrozen zones is a primary concern for the modeling just as it is for more conventional geotechnical engineering problems. That a centrifuge might be an applicable modeling tool is then apparent, and the many geotechnical phenomena that have been successfully modeled, such as load and deformation mechanisms, transient, steady state, and capillary water flow, and convective heat flow, become directly applicable to frozen ground models that contain zones of unfrozen soil. An implicit requirement of such models, however, is that soil freezing and thawing processes must also be successfully modeled. If centrifuge modeling was found to be a valid technique for these processes, then several combined frozen and unfrozen soil problems would be candidates for modeling research. For example, the study and modeling of geotechnical structures that include frost heave and thaw weakening mechanisms would be enhanced.

99. For models comprised solely of frozen soil, rather than of zones of frozen and unfrozen soil, the influence of body stresses on the structural response can be quantified by testing identical small scale models both in a

centrifugal force field and in Earth's gravity field. It is important to model gravity when the gravity-induced weight stresses influence the prototype response. The question for frozen soil structures is whether or not the weight stresses and the frictional components of material strength are significant, relative to the stresses of other loads and to the material cohesive strength, such that the model response is affected. Because such comparisons have yet to be conducted, it is premature to suggest that the centrifuge would or would not be a necessary tool for the modeling of all such structures. Problems that might be studied in completely frozen models include foundations and tunnels in permafrost. In a postfailure condition, if the prototype consisted of a fractured mass with a number of frozen soil blocks, and frictional stresses dominated the block interface stresses, then centrifuge modeling would be appropriate.

100. Cold regions engineering problems that can be studied using models without any frozen soil include those related to the scour of unfrozen sea sediments caused by icebergs, and studies of thaw-induced pipeline settlement when the emphasis is on the pipeline response. Research into the latter problem has been conducted by Vinson and Palmer (1988) who simulated the effect of thaw settlement on a pipeline using a substitute compressible material in place of thawing soil.

Modeling Concepts and Scale Factors

Scale effects and use of prototype material in the model

101. For conventional modeling, the practice of using prototype soils in centrifuge models is an accepted practice, and is conducted in an attempt to achieve structural response similarity of the model and prototype by ensuring that the constitutive response of the model will be as close as possible to the prototype material response. The use of prototype soils within models of typical sizes does not generally result in scale effects unless soils with particles larger than sands are tested. It is common in centrifuge testing to ensure that the parts of models are much larger than the soil particle sizes so that particle size does not result in adverse scale effects. It is also common to use the modeling of models technique to ensure that scale effects are insignificant. There is general agreement that adverse scale effects can

be avoided in geotechnical modeling when using centrifuges of adequate capacity, and there is no reason to expect soil particle scale problems for testing frozen soil.

102. Of concern for testing frozen soil are the potential scale effects associated with freezing or thawing processes. The freezing process, for example, is dominated by a complex set of conditions and processes that occur within a volume of material immediately behind the freezing front, which has been designated as the "frozen fringe." Measurements of the thickness of the frozen fringe in laboratory soil samples indicate that it can be a thin feature and that its thickness is dependent on, among other conditions, the overburden stress, the temperature gradient across the thickness, and the soil type (see, for example, National Research Council 1984). Any adverse scale effects that result from the small prototype of this feature must be evaluated.

103. Another issue is the possibility that, during freezing of a soil in a centrifugal field, ice grains will form at scaled down sizes like that observed by Lovell and Schofield (1986) for sea ice. Here the concern is that, although the soil particles of the model and prototype would be the same size, the ice grains of the model would be smaller than the prototype ice grains, and the constitutive responses of the model and prototype materials might be different as a result. This phenomenon is of particular significance for the segregated ice and ice lenses that can form in frost susceptible soils, and, in conjunction with other freezing processes, may limit a modeler's ability to construct models with prototype proportions and distributions of intergranular and segregated ice. For a soil that is not frost susceptible, construction of models may be enhanced by the limitation that the void sizes of the soil matrix impose on the size of the void-space ice grains, which is in contrast to the generally larger grain sizes of polycrystalline ice (Martin et al. 1981). That is, if the ice grain sizes are mostly dependent on the pore sizes of the soil both for small scale model and prototype soils, and, if the grain sizes do not depend greatly on the stress level under which they are formed, then it is reasonable to expect that scale models can be made that will behave similarly to a prototype.

Viscous effects and
time scale conflicts

104. It is widely recognized from material and structural response measurements that the load and deformation behavior of frozen soil is influenced

by the rate and duration of the load. That is, there are viscous forces that influence the material response. The viscous behavior of frozen soil is typically seen as strain and loading rate effects and as creep. As indicated in Table 1, the time scale factor for viscous phenomena is 1. When the viscous behavior of frozen soil is significant, and when inertial or seepage forces are also significant, time scale conflicts would arise and complete similarity could not be achieved. These issues are discussed here.

105. Frozen soil and ice in the ductile regime are known to increase in strength with an increase in strain rate. The mode of failure may also change. For example, the response of water-saturated frozen sand may become brittle with an increase in strain rate (Shibata et al. 1985). These are important concerns when the inertial and diffusion time scales are required for interpretation of a model's response and when designing a quasi-static experiment such that the loading and strain rates of the model properly represent the loading and strain rates of the prototype. Geotechnical modelers have experience with these issues from a variety of experiments with clay soils. Craig (1983) has described modeling limitations that are related to the viscous nature of clays. Similar limitations would apply to frozen soil modeling.

106. For modeling dynamic events for inertial similarity with a model that is $1/n$ the size of the prototype, the time scale is equal to the length scale $1/n$, and the model loading rate is increased by n. For strains to be equal in the model and prototype, the strain rate will increase by the factor n; whereas, the deformation rate is the same as in the prototype (Craig 1983). Because of the effect that strain rate has on frozen soil behavior, it should be expected that a frozen soil model response may not adequately represent the prototype performance for such a test. For modeling quasi-static loading events for which diffusion processes such as consolidation or heat diffusion occur simultaneously, the time scale would be $1/n^2$, and the prototype time would be interpreted from the model time using this scale factor. The model loading would be applied consistently with this time scale, which would result in a strain rate that is n^2 greater than the prototype strain rate. Strain rate effects on the material response might invalidate such a modeling effort. Additional conflicts arise when modeling dynamic events for which diffusion processes occur simultaneously. However, these issues are typical of the conflicts that arise in centrifuge modeling of unfrozen clays, in dynamic

soils modeling, and in modeling in general, and should be considered not as stifling concerns but as limitations for modeling and as issues that guide modeling design decisions.

107. In addition to the influence of strain rate on the material response, the creep behavior of frozen soil structures and the viscous time scale impose further limitations on modeling capabilities. Two issues of concern are that the duration of tests required to study creep phenomena is prohibitive, and that creep may occur throughout the duration of experiments that must be interpreted with the diffusion time scale. The time scale conflicts of the second issue are not unlike those discussed above.

108. It is recognized that the creep behavior of frozen soil can dominate the response of frozen soil structures, and that designs can be dictated by the expected long-term creep behavior. Because of the time involved in such experiments, only short duration creep events can be modeled when using the prototype soil in the model and when considering realistic centrifuge experiment durations. This is perhaps the greatest limitation for the use of the centrifuge for practical frozen ground applications.

Conductive and convective heat transfer processes

109. Heat transfer in soils occurs as a conductive or convective diffusion phenomenon. To correctly model the freezing and thawing processes of frozen ground, similarity of these processes must be achieved, suggesting that the model and prototype must be thermally similar. Thermal similarity includes similarity of temperature changes and differences at homologous points, as well as similarity of energy and energy density. Savvidou (1988) has shown that the scale factor for temperature change is 1, and that the time scale factor for conductive and convective heat transfer is $1/n^2$. The scale factors for energy and energy density, as indicated in Table 1, are $1/n^3$, and 1, respectively.

110. Physical models of freezing and thawing processes would include zones of unfrozen soil. As suggested above, this implies that similarity of effective stresses is required, and that the use of a centrifuge would be appropriate. Savvidou (1988) presents results from heat transfer experiments for a small scale model comprised of saturated sand that was tested both at Earth's gravity and in a centrifugal field according to the geotechnical scale factors. The model heat transfer in the 1-g test was dominated by conduction,

i.e., the heat was transferred through the stationary soil particles and pore fluid. The model heat transfer in a 100-g test was dominated by convection, or the transfer of heat by the pore fluid seepage, which is also a diffusion phenomenon. Savvidou presents evidence that the convective mechanism is indeed the correct heat transfer mechanism for the prototype configuration and the material tested. For a finer grained soil, which would have a lower coefficient of permeability, conduction rather than convection may have been the dominant heat transfer mechanism in these experiments. When conduction is the mechanism and no forces are generated, i.e. when there is no coupling between the heat conduction and pore pressure, model experiments could be conducted on a small scale model at 1 g. As Savvidou's results illustrate, however, where there is a possibility that the convective mechanism will dominate, 1-g small scale testing is not appropriate. Such results reveal the gross misinterpretation that can be made when relying on results of geotechnical models that are not stress-similar to the prototype.

Model Size and Acceleration

111. For cold regions applications the criteria discussed in Part I under Model Size and Acceleration must be applied. Considering the current state of knowledge of frozen ground centrifuge modeling, it is anticipated that the selection of size and acceleration levels for near future modeling projects for frozen ground applications will be governed primarily by the requirements of validation studies such as modeling of models and by the need to monitor small volume phenomena such as the processes at a freezing front. These requirements are in contrast to the size and acceleration scaling that are governed simply by prototype dimensions and mass.

112. Centrifuge requirements for cold regions applications span a broad range of model size and centrifuge capacity due to the modeling of models needs. Model sizes would range from 0.5 m × 0.5 m × 0.25 m to 2.0 m × 2.0 m × 2.0 m with centrifuge capacity warranted from 20 g-ton to 820 g-ton. The operational requirements for cold region centrifuge studies are summarized in Table 3.

Previous Experiments and Studies

113. Only a few centrifuge experiments with frozen soil have been conducted, and these are not completely documented in the literature. At Cambridge University, England, a pilot experiment of the thawing-induced settlement of pipelines in frozen ground has been conducted as a proprietary study (Croasdale*). At Ruhr University, Bochum, in the Federal Republic of Germany, Jessberger (1989, 1990) and Güttler** have started an investigation of design problems associated with artificial ground freezing. Centrifuge experiments have been performed to study the frost penetration and heaving process in clay during artificial freezing using a single freeze pipe, and the creep behavior of the frozen soil wall around a shaft excavation. Results from the latter are reproduced in Figure 2.

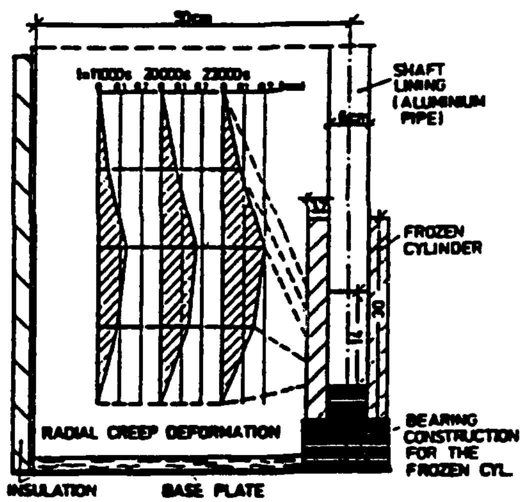

Figure 2. Deformation patterns of a frozen shaft wall measured at three times during a centrifuge model test (Jessberger 1989)

114. Güttler has suggested that the time scale for creep modeling problems may be changed by using substitute materials so that the duration of creep tests can be reduced. By altering the soil strength and the temperature

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* Personal Communication 1990, K. Croasdale, Esso Resources Canada Limited.

** Personal Communication 1990, U. Güttler, Ruhr University, Bochum, Federal Republic of Germany.

of the test, Güttler hypothesizes that the creep rate can be increased for modeling efforts. His comments are preliminary, however, and the hypothesis has not been tested or verified by experiment.

115. Palmer et al. (1985) have discussed the use of the centrifuge for both permafrost and ice engineering problems. They show that the pore water and heat diffusion phenomena can be modeled simultaneously because both phenomena obey the time scale $1/n^2$ and suggest that the centrifuge could be used to model diffusion processes that include a change of state, such as the thawing of permafrost. They further suggest that the centrifuge might be applicable to ice mechanics research, specifically for problems where gravity-induced loads are significant, such as pressure ridge formation in sea ice.

116. Other centrifuge and cold regions researchers have initiated frozen ground studies using centrifuge models without completion of the projects. Scott and Ting (1985) planned experiments and developed equipment for establishing the time scale for soil freezing and heaving and the advantage of using a centrifuge. In 1980, Northwest Alaska Pipelines Company initiated a proprietary centrifuge study in conjunction with the Cold Regions Research Engineering Laboratory (CRREL) of the long-term freezing process around a pipeline in discontinuous permafrost. Neither study advanced to the experimental stage.

117. Researchers in the Soviet Union are known to have conducted centrifuge experiments on permafrost engineering problems (Assur 1990),* but literature citations of these, if they exist, have not yet been found.

118. Experiments of sea surface ice growth have been performed at Cambridge University (Langhorne and Robinson 1983; Lovell and Schofield 1986); at Boeing Aerospace Company (Vinson and Wurst 1985; Clough et al. 1986); and at Ruhr University, Bochum (Güttler 1990).** Lovell and Schofield have reported model results scaled to a prototype context, suggesting that an ice sheet of thickness h in a centrifugal field equivalent to ng's can model a prototype ice sheet of thickness nh in Earth's gravity. They report that, for a correct centrifuge model, the strength of the model ice must be the same as the strength of the prototype ice, and indicate that they have grown ice at high gravities with grain sizes that are proportional to realistic prototype

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* Personal Communication, A. Assur, 1990, CRREL.

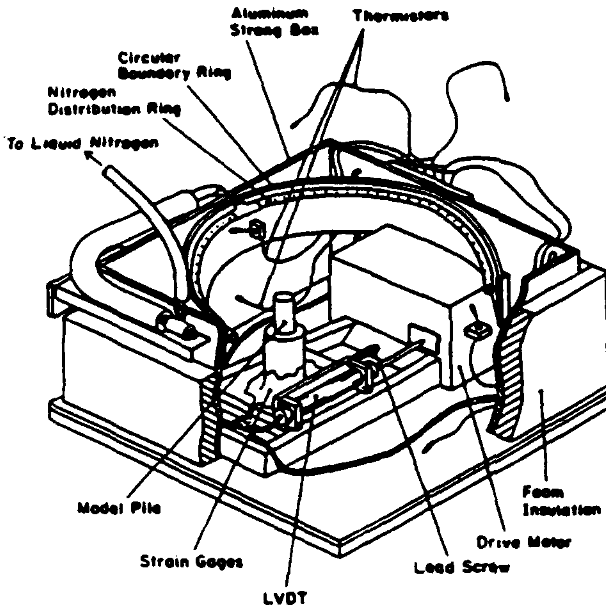
** Personal Communication, 1990, U. Güttler, Federal Republic of Germany.

sizes and depth variations by the scale factor for linear dimension. They further report that the freezing time for models is much less than the freezing time for the corresponding prototype.

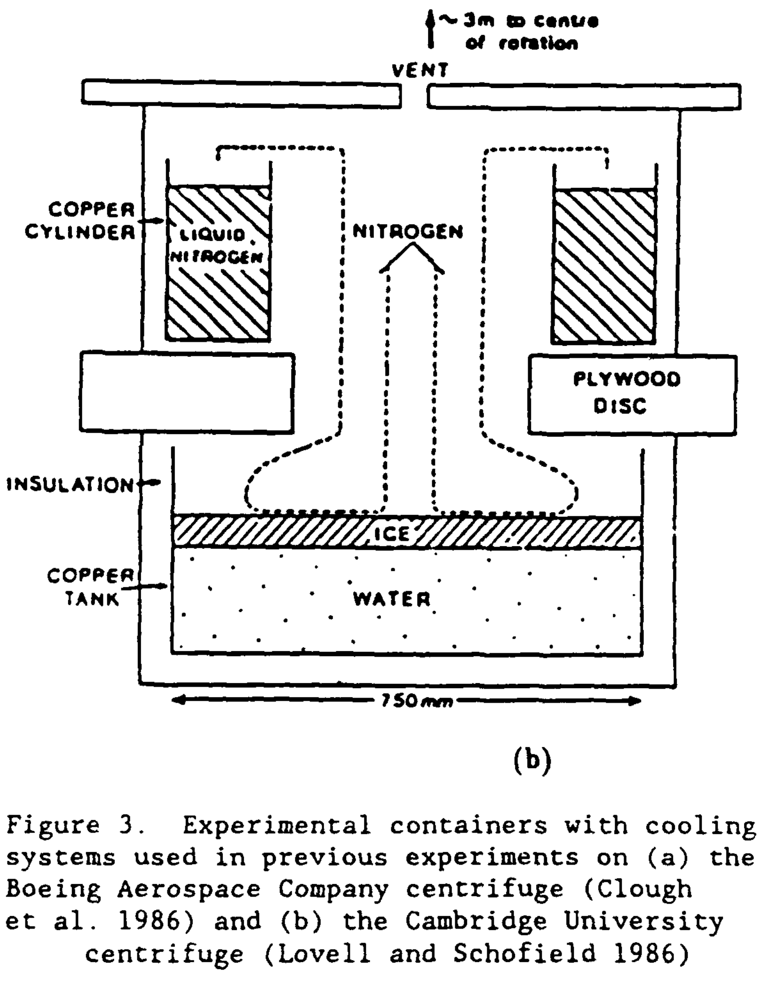
119. Lovell and Schofield (1986), Vinson and Wurst (1985), and Clough et al. (1986) report results of vertical loading tests and horizontal loading tests on centrifuge sea surface ice models. Lovell and Schofield tested ice sheets under a vertical static load, and Vinson and Wurst and Clough et al. tested ice sheets by moving them laterally past a fixed model pile. Both Lovell and Schofield and Clough et al. present data that compare reasonably well with prototype results. Clough et al. suggest that "results obtained from centrifuge model experiments can accurately predict ice forces on large-scale structures," although the significance of gravity-induced stresses within an ice sheet during the movement of the ice sheet past a pile is not made clear by their results or by those presented by Vinson and Wurst. It would be prudent to conduct more research on this problem before emphasizing centrifuge results in a design scenario.

120. The centrifuge hardware used for the ice mechanics and frozen ground engineering experiments ranges from cooling systems developed for existing small and medium sized centrifuges to large centrifuges constructed with built-in cold testing capabilities. Clough et al. (1986) and Lovell and Schofield (1986) describe insulated packages that allow a cold atmosphere to be generated over the surface of a model. These systems, which were developed for the 70 g-ton Boeing centrifuge and the 140 g-ton Cambridge centrifuge, respectively, are depicted in Figure 3. Both use liquid nitrogen to create the cold atmosphere. Schofield and Taylor (1988) have suggested that liquid carbon dioxide can also be used for ice formation. Jessberger and Güttler (1988) describe the development of a 500 g-ton geotechnical centrifuge with an elaborate liquid nitrogen supply system included as original equipment for cold experiments. Figure 4 illustrates this system.

121. For small scale ice mechanics experiments conducted at 1 g, modeling principles have been utilized at CRREL and elsewhere (Ashton 1986). To date, model tests have been conducted to study ice breaking by ships, ice jams in rivers, bearing capacity of floating ice sheets, and ice-structure interaction. For most of these problems, gravity forces play a significant role. To account for the different scale factors of the weight forces and the ice



(a)



(b)

Figure 3. Experimental containers with cooling systems used in previous experiments on (a) the Boeing Aerospace Company centrifuge (Clough et al. 1986) and (b) the Cambridge University centrifuge (Lovell and Schofield 1986)

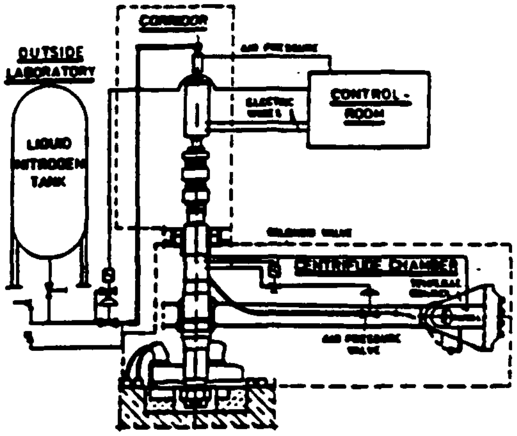


Figure 4. Liquid nitrogen supply system of the Ruhr University, Bochum, centrifuge (Jessberger and Güttler 1988)

failure forces that would exist if the prototype material was used in the model, experimenters have used substitute and artificial ice with strength and elastic modulus values that are reduced by the model scale factor so that the ice breaking forces and the weight forces can be considered to have the same scale factor. In contrast, modeling principles have not been significantly utilized for small scale frozen ground experiments conducted at 1 g. Makin (1966) discusses property scaling and criteria for similarity for the 1-g modeling problem of laterally loaded piles in permafrost, but does not present experimental results.

PART IV: CENTRIFUGE APPLICATIONS IN ENVIRONMENTAL RESEARCH

Introduction

122. Current research in environmental engineering spans many disciplines and subjects from civil, environmental, chemical, and military engineering to the physical, chemical, biological, and social sciences. Within this spectrum, there are a number of potential applications for a centrifuge. Most uses will occur in the engineering disciplines, although some applications in the sciences may be found.

123. It should be remembered that the centrifuge is, in a sense, the researcher's "time machine" in that it can be used very successfully to observe and predict time-dependent phenomena. Although this very powerful research tool can be used to verify many theoretical and numerical models, it is limited by its very nature to use with gravity-driven processes.

124. In the following paragraphs, several potential uses of the centrifuge are presented. These include capping of dredged material deposits, dredged material mound behavior, engineering aspects of wetland creation, detection of ground surface disturbance, and contaminant migration. As knowledge of centrifuge capabilities is gained by WES researchers and as more diverse uses of the centrifuge are proved by various users, additional applications in environmental engineering will likely be identified.

Capping of Dredged Material Deposits

Background

125. The Corps of Engineers is responsible for dredging almost 500 million cu yd of sediment from the navigable waters of the Unites States annually. Approximately 60 percent of this material is placed in aquatic disposal sites (principally in the oceans abutting our shores and the Great Lakes). Although some aquatic disposal sites are dispersive in nature (dredged material is eroded from the site), others are accumulative sites (nonerosive). At the accumulative sites, dredged material may be placed on a level-bottom site to form a mound or it may be placed in a depression for what is referred to as "contained aquatic disposal."

126. When contaminated sediments are placed at accumulative aquatic disposal sites, the deposit of contaminated material is usually covered with uncontaminated (clean) material to isolate the contaminants from the overlying environment. This procedure is referred to as "capping." Although this method of disposal has been used and accepted worldwide as technically feasible, some questions remain regarding the long-term integrity of capped deposits. Specific issues of interest include the initial ability of the typically soft contaminated material to support the weight of the clean capping material, the degree of intermixing of cap and contaminated material at their interface, and cap stability under storm events.

127. Because of the location of capped dredged material deposits (typically under 15 to 90 m of water), actual visual observation and evaluation of field deposits are difficult and, to date, have been limited to remote sensing techniques and minimal diver observation. Costs of intensive monitoring of such field sites are prohibitive. Full-scaled model tests would also be prohibitively expensive unless conducted as a part of an ongoing dredging operation. If conducted in conjunction with dredging operations, the parameters to be investigated would be limited as would the number of tests to be conducted.

Centrifuge applications

128. Each of the above issues could be much more effectively addressed through a centrifugal research effort than through field evaluations or full-scaled model tests. Use of the centrifuge would allow scientific study of numerous aspects of capped deposit behavior under controlled conditions. The following studies would allow more quantitative assessment of the feasibility of using aquatic disposal for contaminated sediments:

- a. Effects of compatibility of material types (sand cap over clay, sand cap over silt, silt cap over clay, etc.).
- b. Effectiveness of noncohesive versus cohesive capping materials (ability to uniformly cover the contaminated material and effect of surface roughness on erosion of cap).
- c. Effects of initial dredged material consistency on cap contaminated material interface.
- d. Effects of mound slopes on deposit stability (also addressing the question of what slope angles are attainable in dredged material mounds).
- e. Effects of cap placement methods (instantaneous dump versus slow release).
- f. Effects of cap stability under different wave climates.

Results of such centrifuge studies would likely allow for more scientific regulation of aquatic disposal, calm the concerns of many environmental groups, and, if necessary, provide data for reassessing aquatic construction techniques.

Dredged Material Mound Behavior

Background

129. There are several issues specific to aquatic dredged material mounds which should be addressed. These include long-term slope stability of soft materials (including the effect of capping), effect of material type and placement consistency on slope angle attained, quantification of phenomena causing reduction of mound surface elevation (erosion versus consolidation), and significance of multidimensional consolidation versus one-dimensional consolidation.

130. As discussed previously, the logistics and cost of conducting field monitoring of aquatic dredged material disposal sites severely limit data collection, analysis, and evaluation efforts. Thus, the centrifuge would be a viable alternative for investigating various aspects of dredged material mound behavior.

Centrifuge applications

131. Particular areas for investigation using the centrifuge include:

- a. Stability of hydraulically dredged material (both with and without caps of various materials).
- b. Stability of mechanically dredged material (both with and without caps of various materials).
- c. Stability of capped versus uncapped mounds of similar geometry and composition.
- d. Effects of storm-generated waves on mound stability.
- e. Quantification of consolidation to be expected for different mound geometries and materials.
- f. Quantification of foundation consolidation resulting from mound construction.
- g. Validation of existing two-dimensional consolidation theory for dredged material mounds.

Wetland Creation

Background

132. Increased emphasis has recently been placed on preservation, restoration, and creation of wetlands. As studies are undertaken to better understand the processes which affect wetlands, physical, chemical, and biological aspects of wetlands must be investigated.

133. Many aspects of wetlands must be investigated in the field because of the complex interactions of the biological and chemical aspects with the physical processes. This will require significant investments of time and money in not only constructing and planting field sites but also in long-term monitoring and evaluation. Thus, any aspects of wetland creation which could be investigated using the centrifuge would minimize the requirements for numerous field sites while providing a thorough well-rounded research program.

Centrifuge applications

134. Some physical aspects of wetland creation could be investigated using the centrifuge. These include methods of material placement to achieve required final elevations, effects of material type and placement technique on development of pools and channels, time frame needed to reach a stable configuration (without vegetation), and possibly others.

135. The centrifuge would allow observation and evaluation of actual physical placement of dredge/fill material for wetland creation. Controlled experiments would permit experimentation, measurement, and analysis of wetlands performance for various wetland types, placement techniques (conventional borrow and fill, hydraulic dredging, mechanical dredging, etc.), and material types (sand, silt, clay, peat, etc.). The development of pools and channels within a developing wetland could be observed, and guidance could be developed on methods for attaining appropriate surface features in the field.

Detection of Ground Surface Disturbance

Background

136. In military operations, it is desirable to have the capability to detect recent ground disturbance. This capability could be used to determine the presence of buried enemy mines or other concealed devices. It may also be useful to determine the time-frame for return of disturbed soils to their

original condition; this could provide guidance on the length of time enemy devices have been installed and, possibly more important, the length of time our buried devices may be susceptible to detection. Since the centrifuge is a type of "time machine", it could potentially be used to evaluate these phenomena.

Centrifuge applications

137. Use of a centrifuge may facilitate expedient analysis of ground surface disturbance since field evaluations would likely require tens of years to complete. Thus, by utilizing the centrifuge, the time required for surface soils to return to an "undisturbed" condition could potentially be evaluated for various earth material types. Also, the surveillance methods required to detect ground disturbance at various times might possibly be evaluated.

Contaminant Migration

Background

138. Movement of various chemical contaminants through geotechnical materials is of interest and concern in many geographic, administrative, and professional areas today. Investigations of effects of contaminant concentration, movement, and diffusion rate have been conducted by WES for numerous applications. Laboratory tests and procedures for predicting contaminant migration rates and concentrations, as well as predictive numerical models and methods for containing contaminants have been developed by WES scientists and engineers.

139. Although significant strides have been made in recent years regarding isolation, prediction, and monitoring of contaminant migration, there are potential uses for a centrifuge in this subject. Potential areas of application are as a tool in design of disposal facilities, prediction apriori of potential for contaminant migration away from a containment site, and determination of the extent and rate of contaminant movement for clean-up operations. In conjunction with these types of investigations, a significant amount of basic research will be required to develop the mechanics and limits of the centrifuge to contaminant migration studies.

140. Researchers are divided in their opinions regarding the applicability of the centrifuge to the geochemical processes involved in contaminant migration and leachate studies. There is serious concern about the

potential for investigating geochemical processes in a physical model with leachate contaminants that adsorb and desorb from geotechnical materials. The kinetics of adsorption/desorption of metal and organic contaminants may not be enhanced using the centrifuge. Basic research would be required to investigate the variables controlling leaching of metals and organics.

Centrifuge applications

141. If the basic research and contaminant migration studies are proved successful, the following types of studies could be conducted:

- a. Evaluation of leachates from contaminated dredged material (both wet and dry dredged material should be investigated).
- b. Evaluation of leachates from composting of TNT and munitions wastes.
- c. Evaluation of leachates from hazardous waste solidification processes.
- d. Weathering effects on solidified waste and subsequent leachate.
- e. Comparison of centrifuge results with those from leachate numerical models.
- f. Horizontal migration of contaminants in wetland soils.

Model Size and Acceleration

142. Table 3 summarizes the centrifuge requirements as envisaged for environmental research. Dredged material deposits can range up to several hundred meters in lateral dimensions and usually less than 15 m high. In order to adequately model a representative portion of a dredged material mound for investigating such topics as capping, material compatibilities, stability, deformation and consolidation in the foundation as well as within the mound, and overall behavior, large centrifuge models are warranted. To study wetland creation and behavior, large models are desired to represent large surface areas 150 to 300 m in prototype dimensions. For contaminant migration studies, large models representing prototype dimensions up to several hundred meters lateral and a few hundred meters in depth are desired coupled with high acceleration so that time effects can be modeled over hundreds or thousands of years.

PART V: CENTRIFUGE APPLICATIONS IN GEOTECHNICAL ENGINEERING RESEARCH

Introduction

Preface

143. The purpose of this part of the report is to present an overview of potential applications of the proposed WES centrifuge in the field of geotechnical engineering. Centrifuge applications are divided into five main technical areas: (a) soil and rock mechanics, (b) mobility, (c) earthquake engineering and dynamics, (d) geosciences, and (e) pavements. Discussed are those areas where centrifuge testing would greatly benefit research objectives in geotechnical engineering particularly in cases where prototype data are expensive to acquire (e.g., for pavement behavior) and almost impossible to acquire (e.g., for earthquake response of earth structures and foundations).

General discussion

144. The behavior of earth materials is complex and highly nonlinear which makes it difficult to predict with confidence the response of an earth structure or soil-structure system. Physical modeling is an approach to solving difficult engineering problems and for numerical analysis verification and development. However, for earth materials, the stress-strain and strength characteristics are stress state dependent and response phenomena (e.g., fluid movement) are time dependent. Therefore, unless small scale physical models create equivalent prototype stress fields, measurements of stress, deformation, pressure, and response or failure mechanisms may be quite different from the prototype. Centrifuge model testing of earth materials and of complicated problems involving them can produce the necessary equivalent prototype stress, strain, and behavior. For the investigation of earth materials and processes, centrifuge model testing offers incredible advantages.

Geotechnical Applications

Soil and rock mechanics

145. Many problems in soil and rock mechanics have been investigated using the centrifuge with varying degrees of success, success being determined by how well similitude was satisfied between model and prototype. It must be stated that perfect fulfillment of similitude is generally impossible except

at a scale ratio of $n = 1$. Fortunately, it is often possible to group dimensional quantities (such as stress, density, energy, etc.) which pose determine an engineering problem into dimensionless ratios and match these ratios between model and prototype to allow extrapolation of prototype behavior from observed model behavior in the absence of perfect similitude. Unfortunately, as the engineering problem to be investigated becomes more complex, it becomes increasingly difficult to satisfy similitude because a larger number of dimensional quantities will be involved in the description of the problem and some terms may appear in several dimensionless ratios in such a manner that it is not possible to satisfy all the conditions of similitude. For example, in Table 1, it is seen that the progression of time on the centrifuge depends on the phenomenon with which it is associated. Obviously, similitude cannot be exactly achieved between model and prototype in engineering problems where dynamic events, diffusion, and viscous flow occur simultaneously. In this sense, some problems may be better simulated on a centrifuge than others. However, with careful design of an experiment and advantageous manipulation of dimensionless ratios, centrifuge modeling can offer insight into engineering problems where none is possible with more conventional means.

146. In recent years, the centrifuge has been used by engineers and scientists around the world to investigate numerous geotechnical engineering problems. Some past investigations are listed in Table 4 for reference. Because soil and rock mechanics problems are related and similar to problems involving ice, snow, and frozen ground, investigations in these area have also been cited and are included in Table 4 along with more standard soil and rock mechanics investigations.

147. Centrifuge modeling applications to soil mechanics problems include:

a. Embankment rehabilitation.

b. Embankment design and stability.

c. Foundation design.

d. Geotechnical aspects of soil-structure interaction problems.

e. Soil trafficability problems.

f. Bearing capacity investigation.

g. Simple and multiple pile performance and design.

h. Retaining wall stability and design.

i. Reinforced earth wall stability and design.

j. Erosion investigations.

k. Consolidation of soil.

l. Settling of high water content/low strength soils.

m. Construction on soft soils.

n. Pore pressure dissipation and drainage in soils.

o. Seepage in soil structures.

p. Modeling of conditions occurring under less than 1 g (one Earth's gravity).

148. It may be necessary to clarify the ratios of modeling conditions occurring under less than one Earth's gravity (such as the gravity levels on the Lunar surface or on Mars) on the centrifuge. Gravity on the Lunar surface is about 1/6 that of Earth's gravity (1/6 g) and on Mars about 2/5 of Earth's gravity (2/5 g). Modeling these conditions of acceleration may be accomplished by using the general definition of n, the scaling ratio. For Lunar surface modeling, for example, n will become equal to the ratio of acceleration on the centrifuge to that of Lunar gravity and the ratio of linear dimension of the Lunar prototype structure to the corresponding linear dimension of the model. In general, any acceleration level (except 0 g) may be represented on a centrifuge by the equation

$$n = \frac{a_c}{a_e} = \frac{L_p}{L_m} \qquad (45)$$

where

n = scaling ratio for any gravity environment

a_c = acceleration generated by the centrifuge

a_e = acceleration in the host environment

L_p = characteristic length in the prototype structure

L_m = corresponding length in the Scale Model

It will not be possible to simulate zero accelerations (except on a centrifuge operating in the 0-g environment of outer space), because a_c in Equation 45 has a lower limit of 1 g in whatever host environment the system operates. As a_e approaches zero, the scaling ratio becomes so large that the model is reduced mathematically to a point and modeling becomes impossible. The selection of n is a necessary part of the design of a centrifuge model experiment and is a balance between the size of scale model desired, the magnitude of

prototype accelerations to be simulated, and the range of centrifuge accelerations available.

149. Planetary geotechnical engineering faces many similar engineering problems as on Earth. Centrifuge testing for planetary soil and rock engineering use and design offers tremendous advantages in yielding equivalent prototype behavior and conditions. Testing could be conducted at near vacuum and near zero humidity, and temperature could be controlled. The modeling of models method of investigation (see Part I, Modeling and Scaling) could be used to provide results in elevated gravity fields, and the trend or performance curve extrapolated to the equivalent prototype response of the planetary gravity field. Figure 5 illustrates a procedure for investigating Lunar behavior. A response at 1 g (Earth) is equal to the response at 6 g (Moon) giving a scale ratio n = 6 for the Moon simulation and the response at 7 g (Earth) is equal to the response at 42 g (Moon) giving a scale ratio of n = 42 for the Moon simulation. Responses can be scaled to the Moon's equivalent prototype using the scaling laws, Table 1. Additionally, the trend developed from the centrifuge tests (e.g., the test data line in Figure 5) can be extrapolated backward to the response in the Moon's gravitational field of 1/6 g (Earth).

150. Applications of the centrifuge to rock mechanics problems include investigation of:

a. Problems in mining (such as subsidence, pillar design, mine stability).

b. Rehabilitation of mines (for example, storage of hazardous and toxic wastes).

c. Failure mechanics in rock (for example, rock burst).

d. Rheologic properties of rock (stress-strain-creep behavior under a given in situ system of stresses).

e. Slope stability.

f. Avalanches.

g. Block behavior.

h. Flow of water within rock masses.

i. Tunneling operations in rock.

j. Rock bolting and anchor systems.

k. Joint behavior.

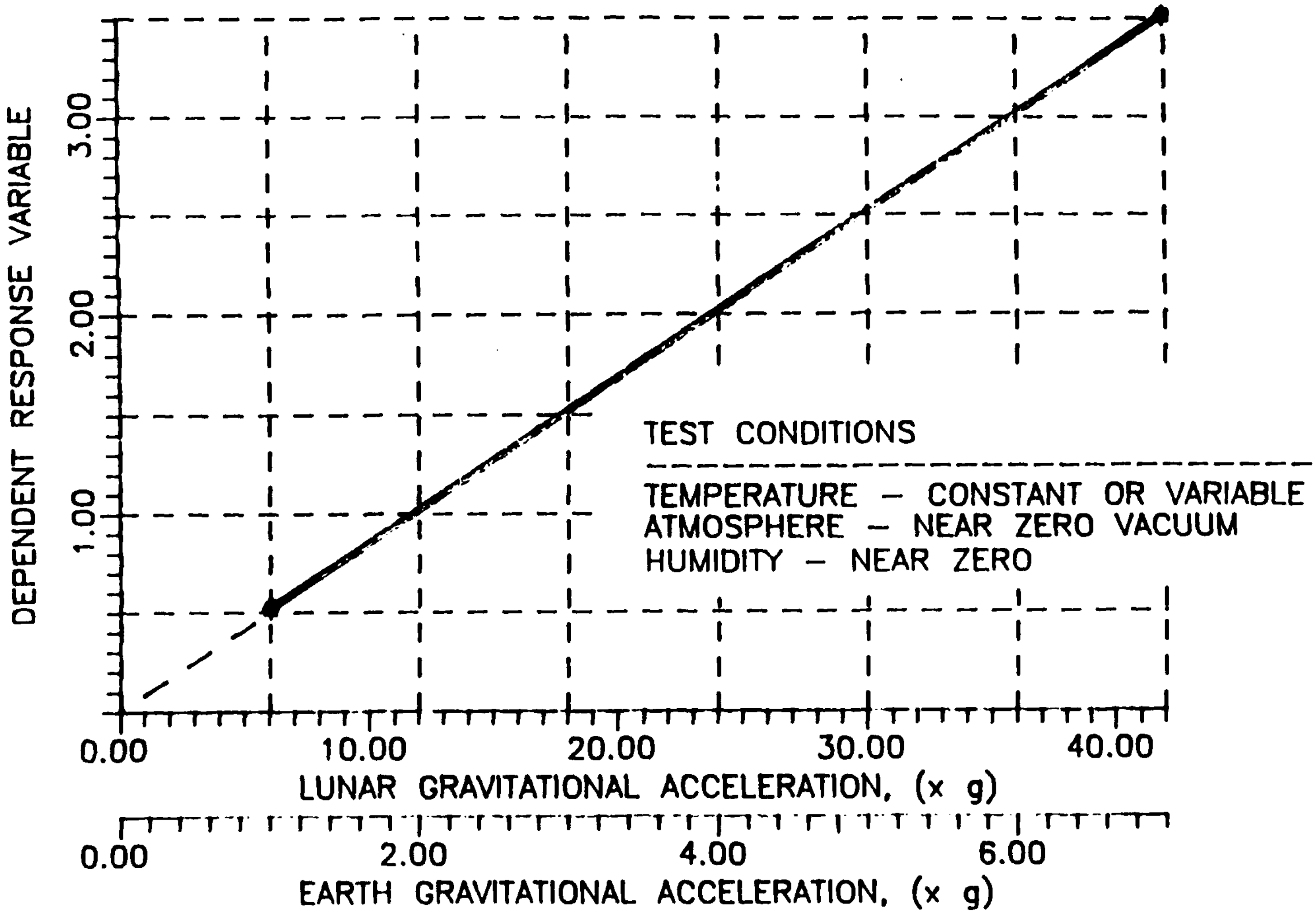


Figure 5. Lunar simulation in a centrifuge

151. The ratio of cost for solution of problems described above either numerical modeling studies or in prototype scale to the cost for developing solutions using centrifuge modeling is unknown because many of the problems described have never been completely solved. It is sufficient to say that the cost savings using centrifuge modeling would be substantial. Field test costs would be hundreds of times that of centrifuge tests.

Mobility

152. Trafficability is of great concern to mobility studies. The trafficability of a soil may be simply defined as the capacity of a soil to resist sinkage and deterioration caused by repeated passes of a given vehicle (or vehicles). Empirical studies have been performed at WES to identify, quantify, and correlate significant factors to the trafficability of military vehicles. Significant factors are vehicle characteristics (such as size, geometry, weight, engine power, suspension system, and vehicle ground contact system) and soil related characteristics, which include strength and material plasticity (texture) not only at the surface but also at depths determined by the response of the soils to the vehicle.

153. Empirical studies and actual field experiences show that repeated passes of a vehicle progressively damage a soil support system. The degree of support system damage and deterioration may progress to the point where traversing vehicles become immobilized. The rate of damage is a function of soil strength which is basically a function of soil plasticity (texture), density, and water content which varies in space, time, and in response to environmental conditions. For example, soil water content is a function of weather conditions and certain other environmental characteristics such as vegetation cover and varies continuously with time.

154. Military vehicle mobility characteristics may be established under controlled prototype conditions with excellent confidence. However, unknown soil and terrain may be encountered in a theater of operations where success will depend, among other things, on speed of movement of personnel and equipment along with precise time synchronization and coordination. Mathematical models have been developed to predict terrain conditions resulting from environmental factors which influence soil strength, but because so many of the reactions involved are not clearly understood, and many of the significant parameters are either unknown or not known with adequate precision, it is

acknowledged that the predictions of such models are not entirely satisfactory.

155. The variation with time of water content (and therefore strength) of a soil will depend on the weather such as air temperature, wind movement, relative humidity, the intensity, duration and amount of rainfall received, the intensity of solar radiation received (which will depend on time of year, location on Earth, cloud cover, and water vapor present in the air), topographic features, and soil characteristics such as plasticity, permeability, and thermal conductivity.

156. Because of the extreme difficulty in mathematically formulating and solving the problem describing soil water content variation (in the spatial sense), physical modeling may offer a viable and perhaps necessary solution. Centrifuge modeling can offer practical and realistic insights to the solution of this problem. In a centrifuge model, a prototype soil could be used, so soil properties such as plasticity, permeability, and thermal conductivity would be matched between model and prototype. On a centrifuge with a properly designed environmental chamber, a given soil profile could be subjected to simulated weather conditions under accelerated time by the application of:

- a. Rainstorms of given intensity and duration.
- b. Solar energy application to simulate any location on Earth and time of year.
- c. Air temperature, humidity, and windspeed.
- d. Ground temperature at depth.

157. The terrain model must include topographic features and the propensity to pond/shed water because the model must be scaled to satisfy geometric similitude. Water seepage and infiltration are phenomena governed by soil permeability and established to behave predictably in the elevated gravity field of the centrifuge. Soil properties such as permeability and thermal conductivity would be combined with the environmental parameters stated above in a set of mathematical relations designed to satisfy similitude as closely as possible.

158. The dimensional quantities determining the water content variation problem are diffusion, surface tension, evaporation rate, transpiration rate, thermal conductivity, density, specific heat, and temperature. These quantities must be arranged into the appropriate dimensionless ratios and manipulated for maximum similitude in the design of the experiment. It must be

mentioned that transpiration does not model on a centrifuge and, in general, its effect cannot be ignored in water content determination in prototype scale. Transpiration does not model with respect to time and it is likely that a time scaling anomaly will exist in the centrifuge modeling of terrain water content determination. The problem of transpiration and its influence on soil water content is not well investigated or understood in prototype scale. Transpiration is a complex phenomenon in that the amount of water lost through this mechanism will be a function of the number, size, distribution, and kind of plants involved as well as the season and prevailing weather conditions. Research would be required to resolve the effect of transpiration on water content determination by centrifuge modeling.

159. It will not be practical to model large areas of terrain in trafficability investigations because of the lack of detailed information on the variation of soil conditions over large areas. Instead, the value of centrifuge modeling for this application will likely be that of evaluating worst-case conditions. Models will be tested at lower acceleration levels (say 20 g) which mean that small areas are modeled, time scalès will be faster than prototype and worst-case weather conditions and soils would be used for model evaluation. A considerable data base of prototype experience has been acquired over the years relating water content convergence with environmental factors, and these data will be used to assist in optimizing the design of a model experiment in which similitude is systematically maintained between model and prototype, although exact fulfillment of similitude is impossible except with a 1:1 scale ratio. By combining similitude theory with practical knowledge of actual prototype behavior, it will be possible to optimize the technique for performing model experiments to obtain the best correlation between model and prototype.

160. Advantages gained are that virtually any combination of conditions could be investigated in a relatively short period of time over virtually any prototype time interval and the parameters influencing strength and trafficability could be measured directly. It should be possible to measure the performance of a given model wheel, drive system, or simulation thereof on a terrain which has been subjected to appropriate environmental conditioning on the centrifuge. The exploration of any combination of circumstances is theoretically possible with an appropriate environmental chamber.

161. Substantial cost and time savings will be realized by using the centrifuge instead of performing prototype experiments. The cost of centrifuge experiments would be small enough and savings in time great enough that several experiments could be performed to bracket terminal water content/soil strength conditions for trafficability. Determining a range of possible solutions is usually required in the investigation of such problems where initial conditions and input conditions (such as weather) are uncertain.

Earthquake engineering and dynamics

162. The ability to resist the effects of earthquakes is especially important for many structures such as power plants, dams, embankments, slopes, offshore facilities, harbor facilities, pipelines, hospitals, and housing. The effects of seismic activity on such structures can only be evaluated by considering the seismic response of the foundation soils and rock and the interactions of the structures (including earth structures) with their foundations. For complete solution of soil and soil-structure interaction problems, the properties and motions of both the foundation and structure must be known, as well as the seismic environment. Analytical model and solution method choices have to be made.

163. Dynamic behavior of soils, soil-structure interaction, and earthquake engineering have been studied extensively for many years. Liquefaction of soils during earthquakes has been extensively studied since the 1964 Niigata, Japan, earthquake which caused classical liquefaction-induced foundation failures. As a result of these research studies, many procedures and models, both simple and sophisticated, have been developed to predict liquefaction and earthquake response. However, the ability to evaluate soil response and soil-interaction is still limited due to a lack of knowledge about seismic ground motions, dynamic soil behavior, and limitations of dynamic analysis methods. Definitive verification of existing techniques is lacking. Complete validation of methods has not been possible because a comprehensive data set for a site that has liquefied and undergone strong shaking is not yet available. There are still uncertainties regarding the liquefaction phenomena and the analytical methods that model it. Until very recently, technology to predict earthquake-induced deformation and postearthquake response was lacking and still needs verification and further developmental studies.

164. Instead of waiting for earthquake field data to be recorded and made available, the alternative is to conduct centrifuge tests on soils and soil-structures of known properties, accurately measure the response phenomena and verify, modify, and calibrate the current technologies. Such testing will complement and fill gaps in existing knowledge and technology and accommodate technological development. The experimental verification of analytical and numerical methods is necessary to provide basic data and to confirm design and evaluation procedures.

165. Numerous US Army facilities around the world, both above and below ground and including critical and noncritical structures, have been and will be constructed in areas of high seismicity. Critical structures include hospitals, dams, power plants, ammunition storage, and other specialized military facilities. Many facilities are subject to vibratory loads caused by traffic, machine vibration, and weapons effects. Dynamic site response criteria and analysis methods are needed to evaluate existing facilities and provide design criteria for new facilities. Rational methods are needed for quantifying decisions concerning potential threat, remedial actions, and new design and construction with regard to seismic and vibratory loadings. Verification and development of criteria and analysis methods are needed in such areas as (a) motion propagation from bedrock through the overlying soils, (b) seismic-induced strains and deformations/settlements, (c) induced pore water pressure and effective stress analysis, (d) soil classification (e.g., damage threshold schemes), and (e) two/three dimensional response analysis of the soil and interacting structures. Additionally, criteria and analysis methods are needed to determine what remedial action should be taken and to establish and guide design for preventive measures against serious damage and loss of life. There are no data concerning the seismic response of earthquake remediation methods or the interaction with surrounding soils or structures. Most of the same needs exist for civil structures as well as those for the military.

166. The cyclic and dynamic response of the foundations of coastal structures and offshore facilities from both explosive-induced water loading and normal wave loading can be studied in the proposed centrifuge. Response of these structures is a function of the pore water pressure behavior, strength degradation, and deformation that occurs in the foundation materials beneath and adjacent to the structures. The behavior of coastal structure foundations is an area where little knowledge exists, where field tests would

be prohibitively expensive, and 1-g models of the foundation materials are not applicable.

167. Field testing to produce performance data and to provide solutions to the above problem areas in earthquake engineering and dynamics (if such tests were feasible) would cost vastly more than centrifuge tests. Additionally, the quality of data and coverage of behavior would be much better and more extensive in centrifuge tests than in prototype testing. As discussed previously, most of the major problems in centrifuge dynamic testing can be overcome.

Geosciences

168. A major centrifuge application is in the numerical model validation and development for groundwater contamination problems and in the hazardous and toxic waste area. The proposed centrifuge will be large enough to study groundwater and pollution problems in both saturated and unsaturated soils extensively in controlled laboratory tests. Studies can be made of problem areas of migration and influencing factors of pollutants, water wells, recharge systems, geologic factors such as different stratigraphies that effect groundwater migrations, migration of the leakage from underground storage tanks, migration of surface contaminants that enter the soils, the behavior of no point source contaminants, and the behavior of different fluid phase systems. As stated previously, time is squared in the centrifuge; 30 years of migration behavior can be simulated in 1 day at 100 g, 3,500 years in 2 weeks at 300 g. Data from centrifuge tests will fill in the gaps where migration data cannot be acquired in the field, and will provide data on time effects and behavior that cannot be achieved in conventional tests. Specific problem applications in diffusion and migration are (a) control of sanitary landfill leachates and gas, (b) management of leaking underground storage tanks, (c) water pollution abatement, (d) management and control of hazardous wastes, and (e) groundwater contamination remediation. Recent work at Cambridge University, England, has shown that migration of pollutants in centrifuge models will occur n^2 times faster than in the prototype. The rate of transfer of material will be n times quicker in the model for both advective and diffusive fluxes which indicates there will be no distortion of the flux transport mechanism. Diagenetic reactions will, if represented by a linear sorption (exchange of components between solid and liquid) model, be a function of the rate of change of concentration of pollutant. Therefore, the

ratio of sorption rate to mass transfer in the centrifuge model will be identical to that in the prototype. Continued developments are needed in the chemical behavior of contaminants in centrifuge testing. An upper bound to the centrifuge testing of pollutants behavior is to address the problem only of migration from one source to another assuming no chemical reactions occur.

169. Groundwater hydraulics for which prototype studies require many years to obtain results can be modeled in a centrifuge in a matter of days or weeks. The proposed centrifuge would have a number of applications that would support the WES groundwater initiative. This initiative seeks to support the Army through research conducted in the area of groundwater processes. The centrifuge would be used to look at and measure flow characteristics for various types of aquifers. These data will then be used to refine and validate numerical models of groundwater movement. Specific examples include groundwater recharge rates, flow through fractured media, and flow through discontinuous media.

170. Other applications in geosciences will be in the studies of geologic structures and phenomena such as faulting, earthquake generation and propagation, and plate tectonics. Such study areas are near impossible to adequately model by other means, and centrifuge modeling would represent a major accomplishment and capability in the geosciences.

Pavements

171. At present, construction and testing of full-scale pavement structures is the most reliable means to determine a given pavement's load deformation characteristics and life. The alternative is to conduct laboratory tests and input the resulting parameters into computer models. Design procedures for both flexible and rigid pavements are based on failure criteria established from full-scaled accelerated traffic tests conducted at different times for specific purposes; they were extremely expensive and time consuming. Current analytical procedures require input from complex laboratory tests. A large number of material parameters are involved which makes it difficult to validate the analytical methods because the outcome of prediction may change significantly by simply varying a laboratory test procedure. The objectives of centrifuge tests of pavement and railroad structures are to (a) predict performance of prototype structures by model tests, (b) validate analytical models, (c) eliminate the need for full-scale tests to extend design criteria for different loadings and materials, and (d) evaluate a wide range of

materials, remediations, and conditions needed for both military and civil applications.

172. Embankments which support pavements and railroad structures are not difficult to model on a centrifuge. However, pavement structural layers of surface and base would be thin and difficult to model. An important consideration will be ensuring that the small-scale model accurately models the characteristics of a pavement structure or rail support structure. Component particle sizes and layer thickness will be important. An alternate to modeling precisely the aggregates and thicknesses may be to conduct tests representative of thicker layers; analytical methods should be applicable to thick structure layers. From a series of thicknesses and/or analytical verification tests, extrapolation could be confidently made to thinner structure layers.

173. When centrifuge modeling of pavement and railroad structures is achieved, model tests could be used as verification of new design and analytical methods. New materials and design concepts could be economically investigated. Applications will include the following:

a. Railroad rehabilitation.

b. Pavement repair and rehabilitation.

c. Layered soils responses to vehicle loading.

d. Geotextile reinforcement for pavement and unsurfaced structures.

e. Alternate materials for pavements.

f. Stabilization of wet soils beneath pavements.

g. Surfacing for container storage areas.

h. Unsurfaced roads and airfield.

i. Pavement and railroad analyses.

j. Soil confinement systems.

k. Overlays.

l. Drainage of base courses.

m. Stabilized base courses.

n. Use of recycled and waste materials.

o. Use of substitute and submarginal materials.

p. Weapons effects breaking pavements.

Another application in the pavements and railroad area is the testing of culverts and verification and modification of design criteria. Present unknowns in need of development for centrifuge testing is how to environmentally age the pavement and railroad structures in the testing process.

Model Size and Acceleration

174. Table 3 summarizes the envisaged centrifuge requirements for geotechnical engineering research. Problems to be studied can range up to very large models and accelerations for such as embankments, dams, retaining structures, rock slopes, and rock behavior. Prototype dimensions could range up to several hundred meters. Studies of geologic processes could require representing over 300 m of material depth. Groundwater studies would require high accelerations to model time over hundreds or thousands of years with sufficient lateral and depth dimensions for adequate study. Platform and container dimensions of approximately 1.5 m should be adequate with accelerations ranging to 500 g.

PART VI: CENTRIFUGE APPLICATIONS IN HYDRAULIC ENGINEERING RESEARCH

Introduction

175. Physical models are widely used in the study of hydraulic engineering projects such as spillways, outlet works, gates, valves, channels rivers, pumping stations, locks, and estuaries. When properly designed and operated according to similarity criteria, these models provide both qualitative and quantitative information about the prototype. These models have focused on the determination of parameters such as velocities, discharge coefficients, head loss, and water-surface profiles. These models have generally served their intended purpose and all have been conducted at normal gravity.

176. A large centrifuge offers the hydraulic engineer another parameter to vary in the effort to achieve similarity between model and prototype. The centrifuge may result in improvements to some of the studies mentioned above or it might allow studies to be conducted that were not previously possible. One of the reasons that centrifuges are not presently being used in hydraulic engineering applications is that most studies will not physically fit within the centrifuge at a suitable scale ratio. While this will continue to be a limiting factor for studies of hydraulic engineering projects such as rivers and estuaries, a large centrifuge platform length (not necessarily payload) will reduce this constraint.

177. There are several areas of hydraulic engineering that remain difficult to physically model and may be benefitted by the ability to increase gravitational forces in the centrifuge. The following are potential centrifuge applications in hydraulic engineering:

a. Surface erosion and protection.

b. Groundwater hydraulics.

c. Fluid-structure interactions.

d. Special studies.

An overview of each of the potential applications follows.

Centrifuge Applications

Surface erosion and protection

178. Surface erosion and protection of erodible boundaries continues to be a high priority concern with the Corps. Surface erosion of noncohesive materials such as riprap are presently best studied in large 1-g models because parameters such as gradation and particle shape are difficult to reproduce in a model that would fit within a centrifuge. Surface erosion of sand size noncohesive material remains difficult in any type of model because the particles presently cannot be easily scaled. Research on particle and fluid scaling in the centrifuge may alleviate this constraint. Sediment transport studies of noncohesive materials may not be significantly advanced by application of a centrifuge. Surface erosion of cohesive materials is one area in which the centrifuge may achieve similarity that cannot be achieved in 1-g models. Previous studies have shown that the requirement to scale particle sizes may not be critical in cohesive soils. A series of feasibility studies on the stability of embankments during overtopping flow were conducted at the University of Colorado under contract to WES (Ko et al. 1989). These types of studies must be conducted with the understanding that several mechanisms are affected when testing is conducted at elevated levels of gravity. Goodings and Schofield (1977) found that mass instability cannot be modeled simultaneously with failure due to erosion. The centrifuge would primarily be used to study two dimensional or section model problems due to the limited space on the centrifuge platform. The modeling of models concept previously discussed would be required to verify similarity considerations.

179. Protection of erodible boundaries continues to be a problem faced by many Corps districts. As stated in the previous paragraph, riprap stability is best determined in large 1-g models. Other protection methods are available, but design guidance is needed to promote their use. Many of these alternate methods cannot be tested in 1-g models because material strength governs stability and only rarely can it be properly scaled in a 1-g model. A large centrifuge offers the potential for producing prototype forces on the alternate bank protection methods at a reduced scale in order to test stability and develop design guidance.

180. Estuary and reservoir studies often require knowledge of the properties of sediment deposits that are not fully consolidated. A centrifuge

could be used to study sediment deposits under various degrees of consolidation.

Groundwater hydraulics

181. Groundwater is the major source of water supply for over 50 percent of our population. Information required for development, evaluation, and protection of our groundwater resources can be obtained using numerical models. A large centrifuge could be used to refine and validate numerical models of groundwater flow processes. Specifically, a centrifuge would be used to observe and measure flow processes associated with coupling of surface and groundwater interactions.

Fluid-structure interactions

182. Adverse fluid-structure interactions in hydraulic structures can result in problems ranging from operational difficulties to failure of the structure. Problems primarily occur at hydraulic control structures such as tainter gates, vertical lift gates, and hurricane surge gates. Model investigations of this type of problem require the proper relationship between the fluid forces and the response of the structure. Presently, 1-g models are used and prototype steel members are constructed of brass in the physical model. Because of the small model forces and the fact that not all of the properties of steel are reproduced by using brass in the model, structural similarity is difficult to achieve. With an adequate water supply and careful scaling of the prototype features to the model, a large centrifuge could be used to produce the correct stress-strain relationship and more closely simulate prototype performance.

Special studies

183. Initial tests on the centrifuge should be conducted to test variation in gravity in some of the fundamental relations used in hydraulic engineering. for example, tests should be conducted with an overflow spillway of known discharge characteristics under a range of gravitational ratios.

184. As stated in the coastal engineering portion of this report, the centrifuge offers the unique ability to study certain problems while achieving equality of two dimensionless force ratios rather than one, which is generally the case in 1-g modeling. Even though this occurs at only a relatively low range of scale ratios, the centrifuge could provide the means for studying components of a system in a manner that would almost be completely free of scale effects. An example application would be in determining the percolation

flow through a rockfill dike or losses through a trashrack or trashscreen. Both of these are normally studied in Froude scale models but are strongly affected by viscous effects. Equality of both Froude and Reynolds numbers in the centrifuge would eliminate significant scale effects.

Model Size and Acceleration

185. Table 3 summarizes the envisaged centrifuge requirements for hydraulic engineering research. Two of the primary requirements for conducting hydraulic engineering applications on the centrifuge are a platform that is long enough to establish proper entrance and exit conditions to the structure being studied and an adequate discharge supply. A length of 10 m is warranted. This long platform length does not necessarily increase the maximum payload of the centrifuge because hydraulic engineering applications will be relatively small in width and particularly in depth. A platform could be constructed for hydraulic engineering applications that would contain a tilting flume, tailgate, flow measurement device, and possibly an on-board pump to provide adequate discharge. This pump and recirculating flume would eliminate the need for a large discharge through the centrifuge arm and also eliminate the problem of disposing of the water from the centrifuge arm.

186. Most hydraulic engineering projects will be studied at relatively small length scale ratios (probably $L_{R,}$ <50), but gravitational scale ratios could vary from equal to the length ratio up to the maximum gravitational ratio of the centrifuge. When centrifuge studies are being conducted with small gravitational ratios, the force of earth's gravity acting normal to the centrifuges acceleration can no longer be considered negligible. This could require some type of device to ensure the appropriate position of the platform so that the resultant gravitational force is in the desired direction.

PART VII: CENTRIFUGE APPLICATIONS IN SOIL-STRUCTURE INTERACTION RESEARCH

Introduction

187. A principal driving force behind centrifuge modeling is the validation of numerical models. With the advent of greatly increased computing power over the last two decades, sophisticated numerical simulations to model prototypes have been developed. Although these numerical simulations provide a wealth of data, in many cases verification of the intricacies of the model against the prototype have not been possible. Often, instrumentation of prototypes has only provided qualitative rather than quantitative agreement with numerical models. Traditional laboratory experimentation has provided specific details on only certain aspects of the numerical models. Scaling effects for laboratory models have been so great that many times the test results are useless as validation of numerical models for application to the prototype. This has left some design engineers apprehensive about relying on the results from numerical models. In numerous studies, numerical models play an important role and it is clear that numerical modeling will be essential to the success of the WES centrifuge.

188. In soil-structure interaction problems, the interests of more than one discipline must be satisfied. The geotechnical engineer is interested in stresses and displacements within the soil mass; whereas, the structural engineer is primarily interested in the shears, moments, and displacements of the structure. Sometimes these different interests are in competition and all disciplines may not always be fully satisfied in the modeling of a problem. Therefore, the primary goal of the investigation must be carefully analyzed. The use of centrifuge modeling for a soil-structure interaction problem will require a team effort of experimental and numerical modelers. Early recognition of this necessary team effort will better prepare WES to successfully use the centrifuge.

Centrifuge Applications

189. Soil-structure interaction problems have long been of interest and concern to engineers. The interaction of the variable and nonlinear soil response and the behavior of a structure is very complex and makes exact analysis difficult. An analytical method is selected that most reasonably approximates reality but still permits a solution to be attained. These analytical procedures must be verified against field observations and prototype performance. This verification is often difficult because of the lack of instrumentation and response measurements of the prototype. Centrifuge modeling will provide a means for verifying many analytical and numerical procedures for soil-structure interaction problems.

190. Soil-structure interaction research areas include pile foundation, gravity earth retaining walls, sheet pile walls, tieback walls, braced excavations, mat foundations, shallow foundations, buried structures, and dams. To illustrate how the WES centrifuge can be used for soil-structure interaction research, the following applications are discussed.

Gravity earth retaining structures

191. These structures rely on their weight to resist the forces exerted by the soil they retain. When conventional methods are used to analyze existing gravity earth retaining walls with clean granular backfills and rock foundations, the results indicate that the walls should be unstable in spite of the fact that they have performed satisfactorily for many years. These findings indicate that assumptions underlying conventional methods may be erroneous for these walls and may lead to excessively conservative results. Research efforts were undertaken to study the fundamental behavior of gravity earth retaining structures using the best available state-of-the-art analysis techniques and to compare the results with conventional analyses as a means of determining why conventional analyses may be overly conservative. To complement the analysis studies, a series of model studies are being conducted to verify the results of the analysis studies. Analyses indicate that the height of wall has a significant effect on the behavior of the structure; however, the model studies are unable to quantify this effect. It should be possible to define this effect at wall height by using a series of centrifuge models that vary the acceleration to simulate different heights of wall.

Stability of pile-supported structures

192. Pile-supported structures that penetrate weak soil layers and are subjected to lateral load must be stable against sliding. To assess the sliding stability of these types of structures, the contribution of the piles to the sliding resistance of a structure must be determined. The key aspect in evaluating the pile resistance is to properly model the interaction between the piles and the soil. The nonlinear interaction for both the vertical and lateral loading on each pile must be considered in modeling the problem. Even if a pile-supported structure is stable, the movements of a weak layer below the foundation need to be taken into account in the design. A research effort is under way to identify the potential modes of failure and the associated mechanisms, and analytical techniques are being developed to assess the modes of failure. The method of verifying these analytical techniques is field performance. Because of the complex nature of the problem, a number of assumptions and approximations must be made for assessment of case studies; therefore, it is only possible to make qualitative comparisons between field performance and analytical models. The proposed centrifuge can be used to corroborate the potential modes of failure and verify the analytical models.

Soil-structure studies of sheet pile walls

193. Sheet pile walls are often added to the tops of levees to gain height needed for flood protection. Determination of the required depth of penetration of the sheet pile is usually based on an adaptation of classical sheet pile cantilever wall design procedures. While walls designed by these procedures have generally performed successfully, it is believed that these procedures are overly conservative and lead to unnecessary added cost to flood protection projects. Research has been conducted for sheet pile walls involving two-dimensional soil-structure interaction finite element analyses of the mechanisms involved in the behavior of typical floodwalls. The finite element analyses revealed that the floodwall problem is more complex than was expected, and behavior is significantly different from that idealized in the conventional design procedures. These observations have led to the development of a new method of analysis that better depicts the behavior of a sheet pile wall atop a levee; however, at the present time, this analysis procedure can only compare finite element studies with a limited number of field tests.

A series of centrifuge model tests could help if not totally verify the validity of this analysis procedure.

Soil-structure studies
at curvilinear conduits

194. Soil-structure interaction effects on buried curvilinear conduits can be determined by investigating the lithostatic load conditions on hydraulic conduits buried in soil under realistic soil-structure interaction pressures. The actual soil pressure loading on buried conduits has not been extensively investigated at prototype scale, and there are still questions about what are realistic soil loading conditions for different shapes of conduits. Tests are envisioned that would enable many qualitative measurements to provide a significant data base of soil loadings that account for actual soil-structure interactions.

Model Size and Acceleration

195. The above centrifuge applications deal with real world problems and require that centrifuge models be scaled from actual prototype dimensions. Using smaller models will not provide sufficient confidence for direct application of the results from centrifuge modeling. To determine the required size of the centrifuge package for modeling the problems outlined above, dimensions of the structures involved and their surrounding foundations were determined as if a numerical model was being developed for them and in consideration of the criteria discussed in Part I.

196. Table 3 summarizes the centrifuge requirements for the above applications in soil-structure interaction research. The maximum platform and container dimension warranted ranges from 1.5 m to 2.0 m at accelerations up to 300 g. Centrifuge capacity warranted ranges from 600 g-ton to 900 g-ton.

PART VIII: CENTRIFUGE APPLICATIONS IN STRUCTURAL RESEARCH

Introduction

197. There are a number of phenomena that are relatively independent of the effects of gravity. For example, the transmission of ground shock through the earth; airblast or watershock propagation, reflection, or rarefaction; the breaching of reinforced concrete walls with demolition charges; the durability of concrete under various environmental conditions; etc. On the other hand, there are many phenomena that are so influenced by gravitational forces that the use of model studies in which the gravity force is unscaled, ranges from questionable in value to completely misleading. To study the effects of nuclear detonations in the earth or against many types of structures, models must be used simply because full-scale tests are not feasible. In other cases, model tests would be much more economical and would allow a much wider variation of the parameters which govern the outcome, but we must rely on a few costly large-scale tests simply because 1-g models will not produce results that are indicative of real world behavior.

198. The ability of a centrifuge to model gravity forces offers a means to overcome both of these problems, and leads to the two great advantages of centrifuge testing--(a) it can provide meaningful model test results in areas where we cannot conduct full-scale tests, and (b) it can provide realistic model results that allow a cost-effective means of developing basic relationships between test variables, even when large or full-scale tests are feasible. The gravity effect is so fundamental that the relationships can usually be easily applied to a wide variation of conditions beyond those that were actually tested; thus, potentially limiting a testing program to only basic testing and research.

Centrifuge Applications

199. Research areas that can potentially benefit from centrifuge testing can be grouped into broad categories of study that correspond to the types of phenomena involved. The first involves those effects that occur in a material that responds in a hydrodynamic manner; i.e., the "flow" of a continuous medium. A primary example is the hydrodynamic flow of earth associated

with the formation of a crater from a nuclear detonation. Related phenomena include surface displacement/subsidence beyond the crater, deep subsurface displacements, residual pore pressures and shock-induced liquefaction, ejecta throw, etc. In wet soils, many of these effects represent "late time" hydrodynamic behavior, after the detonation loads have expired. In any soil (and in rock for very large detonations), the material behaves hydrodynamically during the early and intermediate time periods when the material is under very high stress conditions induced by the blast forces.

200. To accurately reproduce the hydrodynamic behavior of a full-scale event, the model must reproduce a mass (or hydrostatic) load that is in correct proportion to the material properties that provide resistance to the hydrodynamic flow (normally, the material shear strength). The failure to account for such behavior in the past has led to long-standing and costly failures of attempts to correlate the results of full-scale nuclear events with those of smaller tests--including smaller nuclear events. The centrifuge ensures a correct, top-to-bottom incremental distribution of the hydrostatic loads during the hydrodynamic response phase by increasing the mass of each element in a vertical column.

201. The same principle often applies for relatively small explosions such as those from conventional weapons especially if the problem includes the response of a structure within the hydrodynamic field. In this case, it is critical that the mass of the structure be modeled in correct proportion to the forces applied against it by the soil.

202. For problems involving the response of structures to dynamic loads such as seismic motions or low-intensity ground shock from explosions, conventional modeling techniques do not provide a realistic reproduction of the interaction between the soil and the structure foundation, the motion of the structure itself, or the consequent motion-induced stresses within the structure, all because of the inability to properly scale the structure's mass throughout its geometry. By conducting dynamic tests in a large centrifuge, however, the influence of the structure's true mass on its response to the induced shock or motions can be accurately reproduced.

203. For studies of moisture migration through soil, concrete, and other materials, centrifuge testing will reproduce the gravitational "pull" on intergranular water molecules in the same proportion to the resisting force of surface tension that exists in the real world scale. Without the

gravitational boost of the centrifuge, moisture migration in a small-scale model would otherwise be completely dominated to a totally unrealistic degree by the surface tension forces.

204. Other areas of research that could benefit from centrifuge experiments involve behavioral phenomena of discontinuous materials. For rigid structures composed of rock or concrete, it is very difficult to model structural failure in conventional small-scale models because of the inability to scale the influence of the dead weight mass of the structure itself on its response and stability. This becomes a critical limitation in investigations of damage to large structures (such as concrete bridges) from explosive demolition charges, or studies of the stability of tunnels and chambers in jointed rock. With the centrifuge, it will be possible to accurately model the extent of structural failure of demolition-damaged bridge beams or supporting structures by properly simulating the prototype mass of the concrete throughout the structure.

205. For tunnels and chambers in jointed rock, the correct mass scaling for the individual blocks of rock in a joint field will ensure that the wall stresses and displacements in the model tunnel and the tension and shear loads on modeled tunnel supports (such as rock bolts) are accurately reproduced. Furthermore, the ability to scale gravity in the centrifuge will provide the proper "prestressing" of the model tunnel by lithostatic loads allowing a realistic response of the tunnel, surrounding jointed rock, and tunnel supports to the additional dynamic loads from seismic or explosion-induced ground shock effects that are superimposed on the lithostatic loads.

Response of structures to explosive blast and shock effects

206. The centrifuge can be used to evaluate the severity of in-structure shock loads for protective structures from near-miss detonations and conventional weapons as a function of soil-structure interaction and dynamic properties of structure design. The shock effects of conventional-type bursts in a variety of configurations can be simulated with small charges to investigate the effects on in-structure shock. Different types of structures can be modeled (number of bays, floors, plan shapes, depth of burial, etc.) to compare with a few selected prototype and very large-scale model tests to evaluate the importance of soil-structure interaction effects and the dynamic properties of the structure on the severity of in-structure shock.

207. The survivability of buried protective structures can be investigated by developing the capability to model wall and roof resistance/failure for buried protective structures subjected to soil stress loads from below-ground detonations of conventional weapons. Small model studies of blast loadings on protective structures can be conducted, and the damage results compared with those from existing prototype and large-scale model tests. Given a favorable comparison, additional small-scale centrifuge tests could be used to determine qualitative effectiveness of new protective and hardening concepts for vulnerable facilities.

208. The damage to bridges from demolition charges can be investigated by determining the minimum damage to concrete bridge beams and substructures required to ensure loss of load-carrying capabilities. It will be possible to accurately model the extent of structural failure of demolition-damaged bridge beams and supporting structures by simulating the prototype mass of the concrete throughout the structure.

209. The centrifuge can be used to investigate the shock rarefaction effects of surface-reflected precursor waves on direct shock loadings from underwater explosions against submarine hull structures in shallow water with rock bottoms. Gram-scale high explosive charges can be detonated in a shallow water tank. The tank bottom would be composed of high modulus (hence high P-wave speed) concrete to simulate hard rock. Recent studies indicate that the generated peak pressure fields are controlled by precursor waves transmitted through the bottom, which are then radiated back into the water, and are reflected as tensile waves from the water surface. The spallation of the water that results greatly reduces the direct wave impulse from the explosion source. Calculations have shown that the depth and extent of water cavitation is controlled by hydrostatic pressure. Hydrostatic pressures can be simulated in the gram-scale explosive tests in the centrifuge. Miniature pressure transducers can be used to quantify the pressure fields, and high-speed photography can be used to track the precursor, surface-reflected precursor, and the direct shock waves.

Projectile penetration of materials

210. Earth penetrating weapon (EPW) phenomenology studies can be conducted to determine the trajectory of EPW's in various geologic target materials as a function of impact conditions, projectile characteristics, geological layering, and soil properties. The penetration performance of an EPW is a

function of the impact conditions (such as impact velocity, angles of obliquity, and attack), projectile characteristics (such as weight, length, diameter, and nose shape), and target properties (such as shear strength, density, and compressibility). The scaling laws that relate these various parameters to projectile trajectory during deep penetration are not well established, primarily because of the complex effects of gravity on the terradynamic response of the projectile. Systematic full-scale experiments in various geologies to resolve this problem are very costly and not practical. Centrifugal modeling is a cost-effective and practical method for developing accurate scaling laws for predicting projectile penetration into complex geological targets. A factor of main concern in weapon penetration is the terradynamic stability of the projectile and the design of an optimum configuration, consistent with the requirements of the system, for achieving a stable trajectory. The centrifuge provides an expedient means for testing various penetrator design candidates in earth materials of interest and selecting the optimum configuration.

Stability of concrete structures under seismic loadings

211. The seismic response of concrete dams can be studied by determining the response frequencies and amplitudes of concrete dams to specific seismic motion characteristics transmitted through dam foundations. Additionally, earthquake effects on hydraulic intake-outlet works can be investigated by combining soil- and fluid-structure interactions that influence the response of dam intake-outlet structures under earthquake loadings. The earthquake response of lock and dam navigation structures can be investigated by analyzing the risk of damage/failure of lock structures to earthquake motions, particularly as influenced by fluid-structure interactions under controlled cyclic loadings of the lock walls and foundation. Interaction problems require proper modeling of the soil, even if gravity stresses in the dam may be negligible compared with the dynamic stresses. Hence, with proper modeling similitude, the effects on a dam and intake-outlet works of the foundation, embankment, and reservoir characteristics can be investigated to the point of failure. The response of the dam in the nonlinear (or cracked) state is not fully understood, but could be effectively defined with tests conducted in a centrifuge. Also, the effects of joints could be investigated.

Stability of underground structures
in rock under static and dynamic loads

212. The stability of deep-based structures under shock loadings can be studied by investigating the risk of block motion damage to deep underground tunnels and chambers from ground shock loadings produced by nuclear explosions. Model tunnels can be formed in a grid of grout blocks, with the grid simulating a pattern of natural joints in rock. The centrifuge g force will reproduce the lithostatic stress field of a full-scale tunnel environment. A specially designed, small explosive charge at the top of the block array will generate a controlled plane-wave shock passing across the prestressed tunnel area. Strain gages around the tunnel wall will record the lithostatic and dynamic stress distributions around the tunnel perimeter, and flash photography will record the block displacements and shears along the joint planes. The test results can be correlated with the results of computer code calculations of the block motion effects.

213. The earthquake stability of underground structures in jointed rock can be investigated by assessing risk level and extent of damage to tunnels and other underground structures from block motion-related shears and faulting along preexisting joints due to earthquake motions. The modeling concepts would be as discussed in the previous paragraph, except that a vibratory system can be used to excite the base or sides of the block system to simulate a specific cyclic seismic loading.

Response of concrete armor
units to static and impact loads

214. The stability of concrete armor units for breakwater barriers can be studied by determining the stacking stability and stacking stresses for concrete armor units (dolos) as a function of unit size, stacking height and configuration, and concrete strength under realistic static load conditions. The use of the centrifuge would enable engineers to determine a maximum size armor unit that could be used with intended stacking depths and slopes on breakwater faces. The advantage of the centrifuge is that efficient model units (varying from 1/5 to 1/30 scale models) could be used rapidly, where one test could simulate a range of different armor unit sizes because of the scaled g-effect. Immediate applications would solve the stacking problem for concrete dolos armor units. Several model tests could be conducted at less than 1/2 of the cost of one prototype stacking test. Also, the model tests can be conducted to failure by gradually increasing the scaled g-effect until

the model stack fails; whereas, failure in prototype stacking tests is impractical to achieve.

215. The optimum design of concrete armor units to survive drop impact loads can be determined by investigating dynamic stress loads on concrete armor units resulting from drop placement during stacking for breakwater barriers. The use of the centrifuge would enable drop tests to be conducted on a small scale. Since single units would be used, a fairly large scale model could be utilized (1/4 to 1/10) depending on the size of the actual prototype. These tests could evaluate the feasibility of conducting small-scale drop tests as a form of acceptance tests for the dolos units. Other destructive acceptance tests could also be evaluated in the centrifuge.

Lithostatic load effects on
cratering from impacts and explosions

216. The design of shallow underground magazines for explosion containment can be significantly improved by determining minimum rock/soil cover depth required to prevent cover rupture and/or debris throw hazards for accidental explosions in shallow underground ammunition magazines. The amount of ammunition that can be stored in an underground magazine is primarily limited by two hazard effects from an accidental explosion--the extent of the airblast hazard beyond the mouth of the access tunnel, and the extent and amount of debris hazard from rupture of the rock cover over the magazine. The first factor can be reasonably predicted from nonresponding small-scale models; i.e., where the cover depth over the model is much greater than that which could potentially rupture. Small responding models do not produce valid results, because the mass of the cover rock is not scaled in a conventional model. Therefore, the inertia of the rock cover is too small to provide a realistic resistance to the magazine detonation pressure. By conducting small-scale magazine detonation tests in a centrifuge, it will be possible to correctly model the mass and inertia of the rock cover for shallow magazines, and thereby obtain realistic data on the magazine detonation pressures that can be contained by prototype facilities.

217. The centrifuge can also be used for research on cratering on the moon and other planets in support of NASA's space program. The relation of planetary substructure characteristics to impact crater morphology can be investigated by developing correlations to relate impact crater size, shape, and ejecta patterns to the depth and strength characteristics of stratigraphic

layers as a means of inferring planetary geological structure. Previous small-scale explosive cratering tests conducted by WES in geotechnical centrifuges have shown that cratering by energy yields 20,000,000 times the explosive charge energy tested in the centrifuge can be realistically simulated. Model crater morphologies (i.e., crater size, shape, and other physical characteristics) have been produced that are remarkably similar to those of explosion craters on the Earth and impact craters on the Moon, Mars, and Mercury. Since the physical properties and layered structure of the centrifuge specimens resulted in crater morphologies almost identical to those produced by equivalent full-scale explosions in similarly structured geologies, it appears very feasible that such similarities would also apply to the relation between subsurface geological structure and crater morphologies for planetary impact craters. Impact craters could be formed in centrifuge specimens with different geological structures and physical properties, by firing small spherical projectiles into the specimens at high velocities. The relations between the model impact crater morphologies could be used to deduce the subsurface geological structures associated with observed planetary craters of similar morphologies.

Fluid migration in
homogeneous materials

218. Water seepage in concrete structures can be studied by investigating water seepage characteristics in mass concrete as potential freeze/thaw or alkali-silica reaction damage mechanisms. Also, diffusion of hazardous fluids through concrete can be investigated by determining the capability of concrete containment walls for preventing diffusion leakage of hazardous fluids as a function of concrete material properties. Many of the phenomena which can cause damage in mass concrete structures, such as freeze/thaw and alkali-silica reaction, are closely associated with the movement of moisture within concrete. Recent developments in probability-based service life predictions for mass concrete structures depend heavily on a deterministic calculation of critical saturation levels within the concrete. One of the primary means of moisture movement within concrete is seepage, which is governed by the diffusion equation. Finite element methods of calculating seepage in mass concrete are not well developed, and accurate physical modeling would be an invaluable tool in assessing the validity of computational procedures. Because moisture movement in mass concrete structures can be relatively slow, the use of a

centrifuge for physical modeling would allow the equivalent of years of field or laboratory testing to be accomplished in hours, if not minutes. A similar study to investigate the ability of concrete structures to contain certain hazardous and toxic liquid wastes could be performed in the centrifuge to validate analytical solutions.

219. Figures 6-10 illustrate some of the WES early work (1977-1980) involving centrifuge modeling of nuclear explosion effects in soil. Figure 6 shows a soil container designed by WES that was used in Sandia's 8-m radius centrifuge to photographically document the growth and collapse of craters as a function of the soil material properties and the prototype explosion yield. The tests were conducted under loads up to 100 g's, which modeled explosive yields of 100^3 = 1,000,000 times the model charge. Modeling analysis showed that, by reducing the soil resisting force by a factor of 20, the cratering effects of a prototype explosive charge 20,000,000 times the model charge could be simulated.

220. Explosive cratering tests were also conducted by WES in the large geotechnical centrifuge at Cambridge (England) University. Figure 7 shows a crater formed in a cohesive soil at 100 g's using a 4-gm explosive charge. A technique was developed to record the total "flow" displacement of soil around the crater by emplacing barium markers in the soil and x-raying the test specimen after the test (Figure 8). Figure 9 is a Schlierien-type photo showing the contour pattern of stressed soil beneath the crater. Figure 10 shows a crater formed at 100 g's in a granular soil that had a simulated shallow water table of near-saturated material. Very small pressure gages were successfully used to record the dynamic and residual pore pressures produced around the crater by the charge detonation. The pore pressure field corresponded closely to previous measurements made on full-scale tests with charge weights up to 100 tons.

Model Size and Acceleration

221. Table 3 summarizes the centrifuge requirements for the above applications in structural research. The maximum platform and container dimension warranted is 1.8 m at accelerations ranging from 100 g's to 200 g's. Centrifuge capacity warranted ranges from 200 g-ton to 800 g-ton.

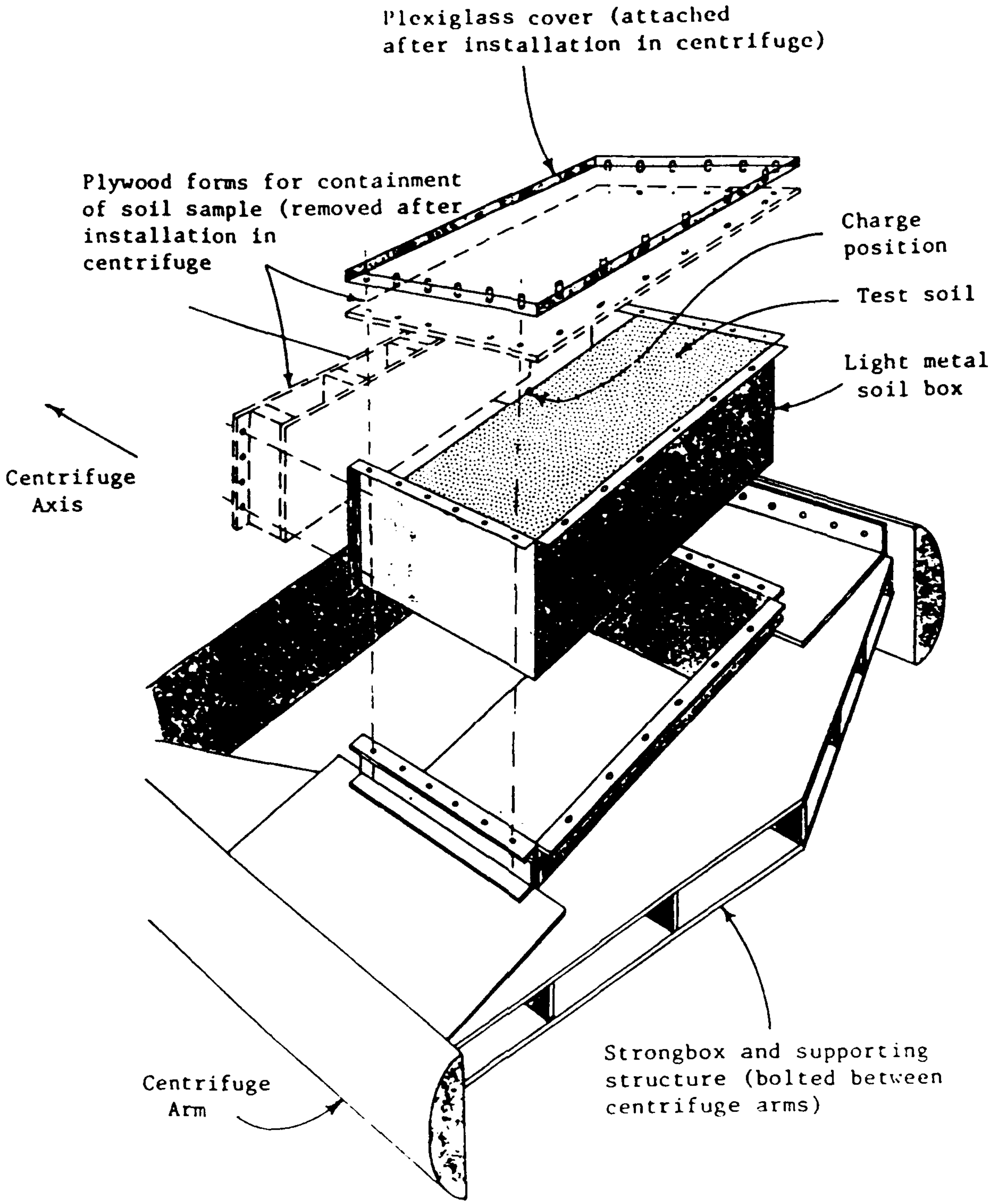
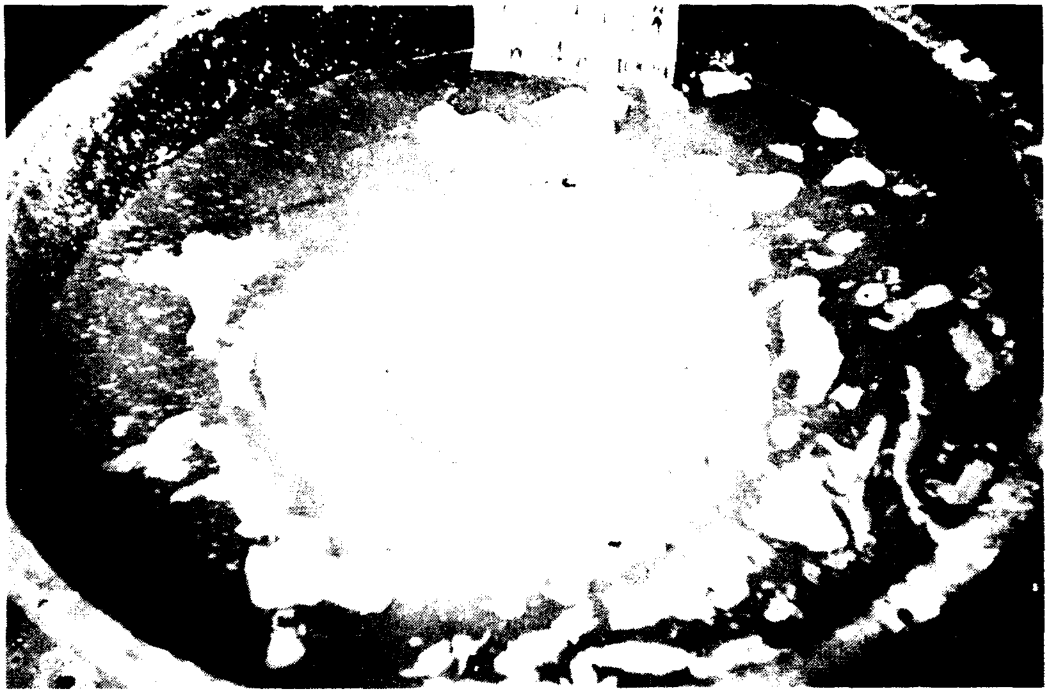


Figure 6. Specimen container designed for photos of WES "half-space" studies of crater formation under high g-loads, using Sandia Lab centrifuge



a. Crater formed in cohesive soil

b. Cut-away of crater in layered soil

Figure 7. Explosive cratering tests conducted by WES in Cambridge University geotechnical centrifuge

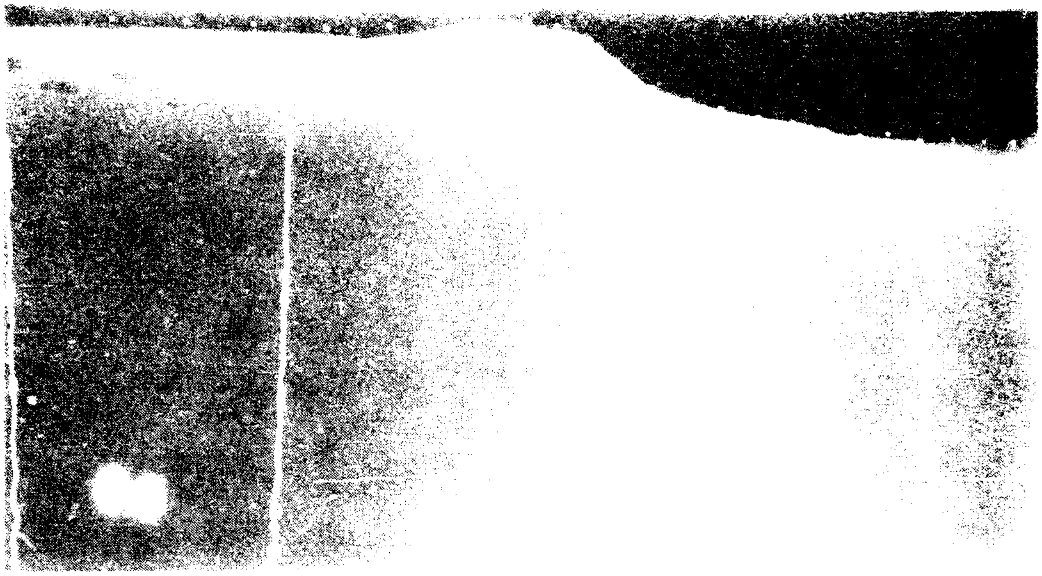


Figure 8. X-ray of centrifuge crater specimen using barium columns to indicate soil flow patterns

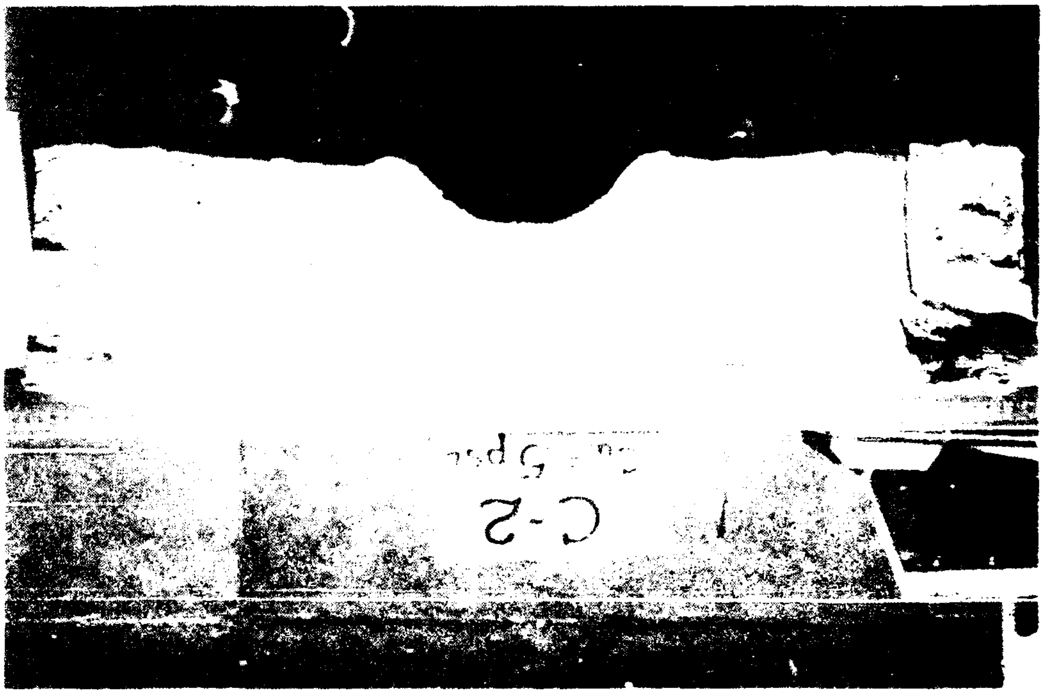


Figure 9. Schlerien type photo of cut-away section of centrifuge crater specimen showing soil stress patterns

Figure 10. Crater formed in fine granular soil with shallow water table, from WES tests using Cambridge centrifuges

PART IX: CENTRIFUGE SPECIAL CAPABILITIES

Introduction

222. The centrifuge will be a large piece of equipment. The system may be designed for durability and constructed of sturdy components, but, because of its size and complexity, it may be likened to a chain with many links, some of which are more fragile than others. Obviously, failure of, or damage to, any of the important links would ultimately lead to system failure, expensive repair, and down time. For this reason it is advisable and desirable to include a special and separate system in the overall design to monitor the health of the centrifuge. This system must be computer based and should consist of (a) computer hardware, (b) sensors to monitor certain parameters, (c) a separate data acquisition system for health parameters, (d) software for health data analysis and decision making, and (e) an interface with system power circuits to effect systematic shutdown if necessary.

223. Parameters dictating the health of the centrifuge which would be monitored by the computer and acquired as data should include items such as (a) main bearing temperature, (b) power consumption by the motors, (c) voltage in various parts of the system, (d) motor temperature, transmission temperature, (e) centrifuge chamber air temperature, (f) strain in the rotor arm (measured at various locations with strain gages), and (g) rotor vibration/unbalance.

224. Other items pertinent to the health of the system will be identified and added to the list as necessary. Norms and ranges of permissible values will be established for each health parameter during initial system use and incorporated into the control system and documenting such information as authorized user, time, and duration of each use. The health monitoring package could additionally protect the system by denying system access to personnel not able to produce appropriate passwords or access codes. Special testing capability needs are discussed in the following sections.

Needed Special Capabilities

Coastal engineering research

225. In addition to wave maker considerations developed and discussed in Part II of this report, hardware is needed for transporting fluid to and from the model while in flight, measuring waves, and measuring behavior of the other model features. Waves generated by whatever mechanism in a high-speed centrifuge will be quite small in amplitude, and have frequencies that could approach 50 Hz or beyond. Conventional wave gages of the resistance or capacitance type are suitable for making measurements of free surface elevations for waves of this size and frequency. However, these types of wave gages may not be able to withstand the high accelerations they will be subjected to in a centrifuge. The thin metallic wires that comprise the wave gage sensor will undergo elastic deformation under the increased gravitational loading, most likely resulting in a failed gage, or at a minimum corrupting the wave measurement. Consequently, it may be necessary to devise new techniques for wave measurement that can withstand the high forces induced in the centrifuge, while still delivering the necessary precision for accurately depicting the wave form.

226. Wave runup of either tsunami or explosion generated waves will also require some forethought on appropriate measurement techniques.

227. Recording of explosion wave gas bubble growth and collapse is probably going to require capability for extremely high speed filming inside the centrifuge test chamber. The methodology has been developed and is also a requirement for any cratering studies conducted in geotechnical materials.

Environmental research

228. Centrifuge capabilities required to support testing in dredged material research include:

- a. Centrifugal model container capable of retaining a pool of water.
- b. Mechanism for placing a slurry into the model container during flight.
- c. Mechanism for placing discrete "dumps" of both cohesive and noncohesive soils during flight (during one flight as many as 10 to 20 "dumps" may be required).
- d. Pore pressure transducers--possibly 10 to 15 connections.
- e. Soil pressure transducers--5 to 10 connections.
- f. Still and video photography equipment.

g. Capability to monitor (small and large) changes in surface height at various locations in the model.

229. Additional requirements to support testing in wetland creation research include:

a. Ability to remove material (simulate bulldozers) to certain elevation.

b. Mechanism for "gentle" material placement (as per dump trucks and bulldozers) during flight.

c. Water supply to inundate the created wetland.

d. Ability to simulate tides--at least periodic rise and fall of water (high and low water).

230. For studies involving ground disturbance, additional requirements are:

a. Ability to place objects in excavation during flight.

b. Ability to replace and compact earth materials during flight.

c. Devices normally used to remotely detect ground disturbance (infrared, etc.).

c. Environmental controls for such as rainfall and temperature.

231. For contaminant migration research, additional requirements include:

a. Mechanism for placing water into the model container during flight.

b. Mechanism for water output sampling.

c. Temperature control for a range of degrees from 4° C to 30° C.

Geotechnical engineering research

232. Provision to acquire and record qualitative information in addition to quantitative data must be made in an overall data acquisition system. The implications of the rapid progression of time and small size of the model are that data must be acquired quickly, precisely on time cue and with good electrical noise rejection if meaningful analyses of the model from acquired data are to be made. Because the model is small, sensors used for internal measurement (such as pressure transducers) must be miniaturized so that model continuity is not disrupted by the presence of sensors which are large relative to the size of the model and the nature of the experiment is unaffected. Fortunately, miniature sensors and transducers are available in the present state of the art and, therefore, research to develop such instruments is not required.

233. Equipment to apply surface forces, surface pressures, surface displacements, vibratory and earthquake loading, and in situ investigations will be required for many geotechnical problems. For certain problems in rock mechanics, flat jacks to apply boundary stresses in orthogonal directions will be required because high lateral stresses frequently exist in rock masses. Lateral stress levels of interest for typical problems may be substantial (up to a maximum of 5,000 to 6,000 psi); therefore, the model container/bucket must be designed to provide reaction for lateral stress application needed in some studies. Additionally, the ability to drill both vertical shafts and horizontal tunnels in flight would be of great advantage in rock mechanics investigations.

234. The disposal of high water content, low strength dredged materials is an important soil mechanics problem. In the prototype, these materials are handled by ponding and processing so that they drain, dewater, solidify, and become useful foundations. Prototype dewatering of dredged materials is slow and the construction procedures used to facilitate drainage are site-specific and determined by trial and error. The centrifuge could be used to great advantage in developing dewatering schemes and would require the capability to perform construction in flight.

235. An additional appliance which would be useful for the investigation of dredged material as well as other important problems in soil/rock/ice mechanics is an environmental chamber in which weather conditions could be simulated. Certain problems could not be completely and adequately modeled without the capability to apply and/or control environmental conditions such as temperature, pressure (including the capability to apply a vacuum), humidity, rainfall, wind movement, and solar insolation. As discussed previously, soil problems on the lunar surface may be represented quite well on a centrifuge. Modeling of gravity levels less than 1 g (as would be the case for the lunar surface) represent no particular problem except that for lunar surface modeling an environmental chamber to allow application of the appropriate temperature and pressure will be required.

236. From the discussions above, the following equipment is recommended for the testing of models to investigate problems in geotechnical engineering:

a. Miniaturized sensors (pressure transducers, stress cells, slope indicators, linear measurement transducers) to avoid disrupting model continuity.

b. A computer based, high speed data acquisition system allowing digitization on the arm to minimize electrical noise contamination of data. For transmission off the arm, fiber optic data transfer is recommended for minimum noise contamination.

c. A photo imaging system to allow mapping of surface displacements. This system should consist of a high speed, high resolution motion picture camera mounted at the axis of rotation (and therefore not subject to high acceleration at the tip of the rotor arm). The camera should be computer controlled so that photos are taken when significant events occur.

d. Miniature hydraulic rams to apply surface forces and displacements to the model. These rams would also be used to load single piles and pile groups on the model.

e. Flat jacks with the capacity to apply lateral stresses up to 6,000 psi along with a specially designed bucket with sufficient stiffness to provide reaction for the load.

f. Equipment to allow movement/excavation of material in flight.

g. Equipment to apply in-flight vibratory and earthquake loading.

h. Equipment and tools for conducting in-flight in situ geotechnical investigations such as cone penetrometer, standard penetration, vane shear, and other types of probes.

i. An environmental chamber to allow application of desired temperature levels to the model as well as the simulation of weather conditions inside the model chamber. The capability to apply vacuum to the model under test will be required for some applications.

j. A computer based and software controlled package to monitor the health of the system which would effect rapid system shutdown if conditions causing equipment damage or failure were detected during centrifuge flight. This package could also be used to control access to system operation.

Hydraulic engineering research

237. Certain features of the centrifuge design should be considered to increase the potential for hydraulic engineering applications. As stated in Part VI, one reason centrifuge modeling has been limited in hydraulic applications is the model size limitations imposed by the size of centrifuges.

238. Adequate water supply and discharge should be provided in the WES centrifuge. The fluid-structure interaction problems described in Part VI would require a large amount of discharge. An example is a hurricane surge gate study where a length ratio of 1:20 might be required to fit the gate on the proposed platform. At this scale ratio the centrifuge model discharge would be 2.5 cfs.

Soil-structure interaction research

239. Structures involve a construction process which has a significant influence on the behavior and response of the structure and the surrounding geological material. For realistic modeling of a soil-structure interaction problem in the WES centrifuge, equipment should be designed to allow for in-flight construction of the structure and associated features. In the modeling of pile foundations, the installation of the pile and the placement of the pile cap must be modeled to obtain a realistic representation of the field conditions. Excavation and/or placement of fill must be simulated, along with the placement of concrete. Dewatering of the construction area would be required for realistic effective stress conditions. All of these construction processes require the development of special procedures and equipment for use in the centrifuge.

240. For blast and shock effects research studies, the centrifuge and model containers must have adequate structural strength to sustain and contain the shock and pressure loading from the modeled explosions.

PART X: CONCLUSIONS

241. A unique centrifuge at WES would place the US Army at the state of the art in physical model testing capabilities and facilitate an economical alternative to field testing. Large 1-g models can be built and tested and field tests can be conducted, but these are expensive and prototype predictions from 1-g model results are difficult if the materials are time, stress, and/or strain state dependent. Centrifuge testing offers cost effective technology to address military and civil problem areas such as:

- a. Nuclear crater scaling laws.
- b. Blast effects on bunkers, lined tunnels, and pile foundations from conventional munitions.
- c. Stability of foundations and earth structures.
- d. Vulnerability of mechanical and electrical systems to conventional threats.
- e. Relative effectiveness of nuclear bursts from earth penetrating weapons and surface bursts.
- f. Groundwater pollution problems.
- g. Efficiency of seepage barriers and other groundwater pollution control or remedial measures.
- h. Constitutive property evaluation.
- i. Static and dynamic soil-structure interaction problems.
- j. Blast effects on surface structures.
- k. Projectile penetration into earth materials.
- l. Pavement structure performance and materials investigations.
- m. Explosive damage to underwater structures.
- n. Planetary engineering in support of NASA's space program.
- o. All earth works; they can be modeled at a fraction of the cost of large-scale or prototype structure tests and include earth and rockfill dams, levees, appurtenant structures, retaining walls, foundations, tunnels, and excavations subjected to a wide range of loadings (including earthquake and vibratory) and parameter variations.
- p. Structural testing.
- q. Material testing and evaluation.
- r. Water-soil-structure interaction.
- s. Frozen soil, water, and ice.
- t. Coastal structures, soil, and waves.
- u. Groundwater behavior.

v. Geologic processes and structures.

The test environment could range from desert to arctic conditions including sea ice problems. Most weapons research testing has been conducted under dry soil conditions; the questions now being asked concern what are the effects of moist and saturated soil conditions and liquefaction behavior. These questions can be addressed in a centrifuge. Most research concerning the above problem areas is done using analytical models because full-scale testing is very expensive; however, centrifuge testing technology offers a very cost effective means for verification of the analytical models. Prototype time and other dependent effects can also be achieved in a centrifuge. A centrifuge is an engineer's "time machine" to future events and behaviors. Table 5 presents a list of centrifuge research investigations that have been conducted by WES.

242. Full-scale destructive tests of structures (including geotechnical structures) are seldom performed because of prohibitive costs and extensive logistical difficulties. The behavior of such structures is generally predicted by mathematical modeling, but this technique is inadequate without verification either by prototype behavior or by complementary physical model testing in a centrifuge or other piece of equipment. In some cases, this is the only way a finite difference or finite element model can be evaluated because variables cannot be sufficiently controlled in some full-scale tests.

243. Among many advantages/benefits of a centrifuge to the USACE are: (a) specific project design studies in areas where calculation methods are not completely reliable or adequate can benefit from prototype behavior predictions, (b) numerical methods of nonlinear continuum mechanics can be validated, improved, or developed based on realistic prototype behavior, and (c) centrifuge tests can be used for parameter studies to find out more about particular properties and material or model responses in relation to variations in loads and boundary conditions. Centrifuge testing will allow the economical proof testing of designs, investigation of problem areas, and validation of numerical methods that have been prohibitively expensive to study with prototype testing. Centrifuge testing will allow the study of important behavior phenomena, including failure, that are impractical or not feasible to induce in prototype situations or for complex problems.

244. Summarized in Table 3 are the operational requirements envisaged by the authors for centrifuge studies in the research application areas discussed in this report. The requirements tabulated represent those needed to

address a broad range of problems or investigations in each research thrust area with actual prototype dimensions and conditions being considered in addition to the criteria discussed in PART I on model size and acceleration. Also tabulated in Table 3 are some of the special testing capabilities required for the research areas.

245. In reviewing Table 3, it must be realized that these requirements are addressing real world problems where structures and conditions can be massive with large dimensions and depths involved and where boundary conditions can be very important. The requirements are addressing problem areas where engineering and scientific knowledge can be probed at its current limits and where engineers and scientists need prototype truth data to extrapolate and verify into the unknown.

246. The current specifications for the existing US large research centrifuges (100 g-ton or larger) and that proposed for WES are shown in Table 6. In order to compare Table 3 with Table 6, four specifications or requirements must be considered; (a) platform/container dimensions, (b) payload, (c) acceleration, and (d) centrifuge capacity. The existing centrifuges in Table 6 generally fall in the low end of the ranges required in Table 3. Table 7 summarizes the capability of the centrifuges in meeting the four specifications or requirements for each of the research thrust areas of Table 3. Requirements were considered met if the capability was within 15 percent of the requirement, which represents no substantive degradation in capability. As can be seen, the requirements for five of the forty research thrust areas are completely met by the existing centrifuges.

247. Thrust area 6 in Table 3 has an upper range of 16 tons payload, which was developed from considerations for studying by modeling of models the artificial freezing process used for soil excavation and considering realistic site dimensions and depths. Because the scale factor for mass in the prototype is n^3 times the model mass (Table 1) only a small shift in the modeling of models sequence of acceleration levels and/or dimensions will bring the test payload within the capabilities of the proposed WES centrifuge with no degradation in the test series. This then will result in the requirements for all forty thrust areas being met by the proposed WES centrifuge.

248. The unique facility at WES would provide a capability to address the Corps military and civil problems in new ways. A centrifuge facility would permit WES to greatly broaden the complexity and types of engineering

problems we research and solve. It would permit us to better serve a larger segment of the Department of Defense as well as other sponsors and would facilitate cooperative agreements between universities, the National Science Foundation, and WES. Finally, the WES would become a national center of expertise for centrifuge modeling in the United States and a recognized authority internationally.

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Table 1

Scaling Relationships

Quantity	Full Scale (Prototype)	Centrifugal Model at $n \times g$
Linear dimension	1	$1/n$
Stress (Force/Area)	1	1
Strain (Displacement/Unit Length)	1	1
Density	1	1
Mass	1	$1/n^3$
Force	1	$1/n^2$
Energy	1	$1/n^3$
Displacement (Distance)	1	$1/n$
Velocity (Distance/Time)	1	1
Acceleration (Distance/Time^2)	1	n
Time		
Dynamic problems	1	$1/n$
Diffusion problems	1	$1/n^2$
Viscous flow problems	1	1
Frequency		
Dynamic problems	1	n

Table 2

Comparisons of Explosion Wave Sealing Relationships

Parameter	Reduced Pressure	Increased Gravity	$N_L = n$
Length	N_L	N_L	N_L
Gravity	1	$\frac{1}{n}$	$\frac{1}{N_L}$
Atmospheric pressure	N_L	$\frac{N_L}{n}$	1
Time	$\sqrt{N_L}$	$\sqrt{nN_L}$	N_L
Velocity	$\sqrt{N_L}$	$\sqrt{\frac{N_L}{n}}$	1
Acceleration	1	$\frac{1}{n}$	$\frac{1}{N_L}$
Natural frequency	$\sqrt{\frac{1}{N_L}}$	$\sqrt{\frac{1}{nN_L}}$	$\frac{1}{N_L}$
Energy	N_L^4	$N_g N_L^4$	N_L^3
Wave speed	N_L	$\sqrt{\frac{N_L}{n}}$	1
Vapor pressure	N_L	$\frac{N_L}{n}$	1

Table 3

Summary of Operational Requirements for Centrifuge Studies

No.	Research Thrust	Required Platform/ Container Dimensions (m)	Payload Weight Tons	Required Test Acceleration (g's)	Required Centrifuge Capacity (g-ton)	Required Special Centrifuge Testing Capabilities *
1	Explosion Generated Waves	1.5 × 1.5 × 0.5	2.0 - 3.5	150 - 300	500 - 600	a, b, d, p
2	Tsunami Runup	Minimum 1.0 × 1.0 × 0.5	1.5 - 2.0	150 - 400	225 - 800	b, c, d
3	Marine Foundations	1.5 × 1.5 × 2.5	2.0 - 3.0	200 - 300	400 - 900	b, c, d
4	Mechanics of Frozen Ground and Freeze-Thaw Processes	From 0.5 × 0.5 × 0.25 to 2.0 × 2.0 × 1.0	0.6 - 7.5	12 - 400	25 - 820	d, e, f, g
5	Behavior of Facilities and Structures and Interactions with Frozen Ground, Freeze-Thaw Processes and Ice	From 0.5 × 0.5 × 0.25 to 2.0 × 2.0 × 1.0	0.6 - 7.5	12 - 400	25 - 820	d, e, f, g
6	Artificial Freezing Process in Soil	From 0.5 × 0.5 × 0.5 to 2.0 × 2.0 × 2.0	1.0 - 16.0	12 - 100	30 - 800	d, e, f, g
7	Environmental Studies Involving Freezing, Frozen, and Thawing Ground	From 0.5 × 0.5 × 0.25 to 1.6 × 1.6 × 1.0	0.6 - 5.0	12 - 50	20 - 60	d, e, f, g
8	Planetary Studies in Extra-terrestrial Permafrost	1.0 × 1.0 × 1.0	2.0	10 - 200	20 - 400	d, e, f, g, t

* a-y defined at the end of the table.

Table 3 (Continued)

No.	Research Thrust	Required Platform/ Container Dimensions (m)	Payload Weight Tons	Required Test Acceleration (g's)	Required Centrifuge Capacity (g-ton)	Required Special Centrifuge Testing Capabilities *
9	Capping of Dredged Material Deposits	1.0 × 1.0 × 1.0	2.0	100 - 300	200 - 600	d, h, i
10	Dredged Material Mound Behavior	From 1.0 × 1.0 × 1.0 to 2.0 × 2.0 × 1.0	3.0	100 - 300	300 - 900	d, h, i, c
11	Engineering Aspects of Wetland Creation	1.5 × 1.5 × 0.5	2.5	100 - 200	250 - 500	d, h, i, j
12	Contaminant Migration	1.5 × 1.5 × 1.0	2.0 - 5.5	100 - 400	200 - 900	d, g, k
13	Embankment Rehabilitation, Design Stability	1.5 × 1.5 × 1.0	2.0	100 - 300	200 - 600	d, h, n, o, r
14	Foundation Behavior and Design	1.5 × 1.5 × 0.5	2.5	200 - 300	500 - 750	d, h, n, o, r
15	Retaining Wall and Reinforced Earth Wall Stability and Design	1.5 × 1.5 × 1.0	3.0 - 4.5	100 - 300	300 - 900	d, h, n, r
16	Construction on Soft Soils	1.5 × 1.5 × 1.0	2.0	100 - 300	200 - 600	d, h, n, o, r
17	Consolidation, Seepage, and Pore Pressure Behavior	0.6 × 0.6 × 0.5	1.5	100 - 300	150 - 450	d, h, n, r
18	Soil Trafficability	1.5 × 1.5 × 0.5	2.0	100 - 300	200 - 600	d, h, n, r, s, u
19	Planetary Geotechnical Engineering Investigations	1.5 × 1.5 × 1.0	2.0	100 - 300	200 - 600	h, n, r, t, p
20	Mining, Tunneling, Rock Behavior	1.5 × 1.5 × 1.0	2.5 - 6.0	100 - 300	400 - 900	r, v, w, d

Table 3 (Continued)

No.	Research Thrust	Required Platform/ Container Dimensions (m)	Payload Weight Tons	Required Test Acceleration (g's)	Required Centrifuge Capacity (g-ton)	Required Special Centrifuge Testing Capabilities *
21	Rock Slope Stability, Bolting and Anchors, Joint Behavior	1.5 × 1.5 × 1.0	2.5 - 6.0	100 - 300	400 - 900	r, v, d
22	Rock Properties, Failure Mechanics	1.5 × 1.5 × 0.5	2.5 - 6.0	100 - 300	400 - 900	v, d
23	Dynamic Behavior of Soils, Earth Structures, Soil Structure Interaction Earthquake Engineering	1.5 × 1.5 × 1.0	2.5 - 3.5	100 - 300	250 - 900	d, h, n, r, q
24	Groundwater Behavior and Migration	1.5 × 1.5 × 1.0	2.0 - 5.5	200 - 400	200 - 900	d, r, k, h
25	Geologic Structures and Processes	1.5 × 1.5 × 1.0	3.0 - 6.0	100 - 300	300 - 900	h, d, r, v, x
26	Pavements and Railroad Structures	1.5 × 1.0 × 0.5	2.0	10 - 200	20 - 400	h, n, d, r, u
27	Surface Erosion and Protection	3 × 0.6 × 0.5	3.0	10 - 100	30 - 300	l, m, y
28	Fluid-Structure Interaction	3 × 0.6 × 0.5	4.0	10 - 100	40 - 400	l, m, y
29	Special Hydraulic Studies	3 × 0.3 × 0.3	2.5	10 - 300	25 - 750	l, m, y
30	Soil Structure Interaction; Structural Walls	1.5 × 1.5 × 1.0	3.0 - 4.5	200	600 - 900	h, n, d
31	Soil-Structure Interaction; Earth Retaining Structures	1.5 × 1.5 × 1.0	3.0 - 4.5	200	600 - 900	h, n, d
32	Soil-Structure Interaction; Foundations	2.0 × 1.0 × 0.5	2.5	300	750	h, d, o

(Sheet 3 of 5)

Table 3 (Continued)

No.	Research Thrust	Required Platform/ Container Dimensions (m)	Payload Weight Tons	Required Test Acceleration (g's)	Required Centrifuge Capacity (g-ton)	Required Special Centrifuge Testing Capabilities *
33	Soil-Structure Interaction; Buried Conduits and Structures	2.0 × 1.0 × 0.5	2.5	300	750	h, n, d
34	Response of Structures to Explosion Blast and Shock Effects	1.8 × 1.2 × 1.0	4.5	100	450	a, p
35	Projectile Penetration of Materials	1.2 × 1.2 × 1.2	3.5	100	350	a, p
36	Stability of Concrete Structures Under Seismic Loadings	1.8 × 1.2 × 1.0	3.0	150	450	a,q
37	Stability of Underground Structures in Rock Under Static and Dynamic Loads	1.2 × 1.0 × 1.2	3.5	200	700	a p, q
38	Response of Concrete Armor Units to Static and Impact Loads	1.8 × 1.2 × 1.0	2.0	100	200	a, p
39	Lithostatic Load Effects on Cratering From Impacts and Explosions	1.8 × 1.2 × 1.0	4.0	200	800	a, p
40	Fluid Migration in Homogeneous Materials	1.2 × 1.0 × 1.2	2.0	100	200	d, k

Table 3 (Concluded)

a - high speed filming
b - special measurement instruments
c - wave generator
d - water or fluid supply
e - freezing and thawing mechanism
f - insulation
g - temperature control
h - in-flight addition and removal of material
i - simulation of material placement under water
j - tidal simulation
k - in-flight water and soil sampling
l - water discharge and velocity measurements
m - water surface measurements
n - in-flight construction
o - in-flight insertion of piles
p - explosive test conditions
q - vibratory system for earthquake loading
r - in-flight in situ geotechnical and geophysical investigations
s - environmental chamber
t - vacuum condition
u - in-flight load application mechanisms simulating traffic of vehicles
v - in-flight load application mechanisms including flat jacks
w - in-flight tunneling and mining
x - in-flight mechanisms to produce faults, earthquakes, and mass movements
y - large capacity fluid supply and circulating system

Table 4

Examples of Soil and Rock Mechanics Centrifuge Investigations Conducted by Others

Three-dimensional consolidation of soils
Seepage paths and rates in earth structures
Pore pressure dissipation in earth structures
Compression of elastic and visco-elastic materials
Transient flows of pore fluids in porous media
Stress-strain relationships
Anisotropic effects in nonhomogeneous media
Stability of slopes in earth materials
Foundation settlement and displacement
Stability of retaining walls
Consolidation of spoil piles in deep water
Stress-strain relationships in buried pipes and culverts
Bank failure and erosion along large rivers
Stability of embankments on soft clay foundations
Effects of water table drawdown on soil consolidation
Effects of surcharge on soil structures
Effects of flooding on levees, dams, and embankments
Migration of pollutants through porous media
Development of pressure ridges in the polar icepack
Ice rheology
Evaluations of single and clustered pilings
Stability of drilling platforms in marine environments
Self-weight consolidation and stability of mine wastes
Overtopping of earth dams
Settling of slimes in mine tailings ponds
Soft ground tunneling
Suction anchors for drilling platforms
Reinforced earth retaining walls
Water erosion of earth materials
Large strain consolidation of phosphatic wastes
Ice flow failure mechanisms in off-shore structures
Behavior of cemented sand
Behavior of cantilever retaining walls
Drawdown failures in earth embankments

Table 5

WES Centrifuge Investigations

Year	Study	Location
72 - 75	Nuclear Cratering and Liquefaction	University of Cambridge, England
76 - 79	Modelling Slope Failures	University of Cambridge, England
76 - 79	Stability of River Banks and Flood Embankments	University of Cambridge, England
76 - 79	Dynamic Soil-Structure Interaction and Earthquake Behavior	University of Cambridge, England
76 - 79	Behavior of Embankments Under Dynamic Loading	University of Cambridge, England
77 - 80	Nuclear Cratering	Sandia Laboratories, Albuquerque, NM
76 - 79	Behavior of Retorted Oil Shale	University of Cambridge, England
79 - 82	Response of Clay Embankments to Earthquakes	University of Cambridge, England
81 - 84	Dam Overtopping	University of Colorado, Boulder, CO
82 - 84	Stability of Embankments on Soft Clay	University of Cambridge, England
83 - 88	Earthquake-Induced Liquefaction, Deformations and Behavior, and Dynamic Soil-Structure Interaction	University of Cambridge, England

Table 6

United States Large Research Centrifuges

Centrifuge	Radius (m)	Platform/ Container Dimensions (m)	Max Payload (tons)	Max Acceleration (g's)	Current Capacity Rating (g-ton)
University of Colorado, Boulder *	5.5	1.2 × 1.2 × 0.9	2.2	200	440
University of California at Davis *	9.1	2.1 × 1.8 × 1.5	4.0	50	200
Rensselaer Polytechnic Institute *	2.8	0.8 × 1.0 × 0.8	1.0	200	100
Sandia National Laboratories *	7.3	1.2 × 0.2 × 0.9	2.0	150	300
USAE Waterways Experiment Station, Proposed	6.5	1.8 × 1.3 ×1.1/2.3 to 2.6 × 1.3 ×1.1/2.3	6.6	350	772

* Not presently equipped for: (a) large model earthquake or vibration testing, (b) explosion blast testing except Sandia, (c) model freezing, thawing, and temperature control, (d) large quantities of water input and discharge, (e) wave generator, or (f) with the exception of Colorado, no in-flight balance for allowing adding or subtracting significant mass.

Table 7

United States Centrifuges Meeting the Requirements of Table 3

Research Thrust	Platform/ Container	Payload	Acceleration	Capacity	Complete Match To the Four Requirements
1	CO, CA, WES	CO[B], CA, SA[B], WES	CO[B], RPI[B], SA[B], WES	WES	WES
2	CO, CA, RPI, WES	CO, CA, SA, WES	CO[B], RPI[B], SA[B], WES	CO[B], CA[A], SA[B], WES	WES
3	CO[A], CA[A], WES	CO[B], CA, SA[B], WES	CO[B], RPI[B], WES	CO[B], WES	WES
4	CA, CO[B], RPI[B], SA[B,A], WES	CO[B], CA[B], RPI[B], SA[B], WES	CO[B], CA[B], RPI[B], SA[B], WES	CO[B], CA[B], RPI[B], SA[B], WES	WES
5	CA, CO[B], RPI[B], SA[B,A], WES	CO[B], CA[B], RPI[B], SA[B], WES	CO[B], CA[B], RPI[B], SA[B], WES	CO[B], CA[B], RPI[B], SA[B], WES	WES
6	CA, CO[B], RPI[B], SA[B,A], WES	CO[B], CA[B], RPI[B], SA[B], WES[C]	CO, CA[B], RPI, SA, WES	CO[B], CA[B], RPI[B], SA[B], WES	WES
7	CA, CO[A], RPI[B], SA[B,A], WES	CO[B], CA[B], RPI[B], SA[B], WES	CO, CA, RPI, SA, WES	CO, CA, RPI, SA, WES	WES
8	CO, CA, RPI, WES	CO, CA, SA, WES	CO, CA[B], RPI, SA[B], WES	CO, CA[B], RPI[B], SA[B], WES	CO, WES
9	CO, CA, RPI, WES	CO, CA, SA, WES	CO[B], RPI[B], SA[B], WES	CO[B], CA[B], SA[B], WES	WES
10	CA, CO[B], RPI[B,A], WES	CA, WES	CO[B], RPI[B], SA[B], WES	CO[B], SA[B], WES	WES
11	CO, CA, WES	CO, CA, SA[A], WES	CO, RPI, SA, WES	CO, CA[A], SA[B], WES	CO, WES
12	CO, CA, WES	CO[B], CA[B], SA[B], WES	CO[B], RPI[B], SA[B], WES	CO[B], CA[B], SA[B], WES	WES
13	CO, CA, WES	CO, CA, SA, WES	CO[B], RPI[B], SA[B], WES	CO[B], CA[B], SA[B], WES	WES
14	CO, CA, WES	CO, CA, SA[A] WES	CO[B], RPI[B], WES	WES	WES
15	CO, CA, WES	CA, WES	CO[B], RPI[B], SA[B], WES	CO[B], SA[B], WES	WES
16	CO, CA, WES	CO, CA, SA, WES	CO[B], RPI[B], SA[B], WES	CO[B], CA[B], SA[B], WES	WES
17	CO, CA, RPI, SA[A], WES	CO, CA, RPI[A], SA, WES	CO[B], RPI[B], SA[B], WES	CO, CA[B], RPI[A], SA[B], WES	WES

Table 7 (Continued)

Research Thrust	Platform/ Container	Payload	Acceleration	Capacity	Complete Match To the Four Requirements
18	CO, CA, RPI[A], WES	CO, CA, SA, WES	CO[B], RPI[B], SA[B], WES	CO[B], CA[B], SA[B], WES	WES
19	CO, CA, RPI[A], WES	CO, CA, SA, WES	CO[B], RPI[B], SA[B], WES	CO[B], CA[B], SA[B], WES	WES
20	CO, CA, RPI[A], WES	CO[B], CA[B], WES	CO[B], RPI[B], SA[B], WES	CO[B], WES	WES
21	CO, CA, RPI[A], WES	CO[B], CA[B], WES	CO[B], RPI[B], SA[B], WES	CO[B], WES	WES
22	CO, CA, RPI[A], WES	CO[B], CA[B], WES	CO[B], RPI[B], SA[B], WES	CO[B], WES	WES
23	CO, CA, RPI[A], WES	CO[B,A], CA, WES	CO[B], RPI[B], SA[B], WES	CO[B], CA[A], SA[B], WES	WES
24	CO, CA, RPI[A], WES	CO[B], CA[B], SA[B], WES	CO[B], RPI[B], SA[B], WES	CO[B], CA[B], SA[B], WES	WES
25	CO, CA, RPI[A], WES	CA[B], WES	CO[B], RPI[B], SA[B], WES	CO[B], SA[B], WES	WES
26	CO, CA, RPI[A], WES	CO, CA, SA, WES	CO, CA[B], RPI, SA[B], WES	CO, CA[B], RPI[B], SA[B], WES	CO, WES
27	WES	CA, WES	CO, CA[B], RPI, SA, WES	CO, CA[B], RPI[B], SA, WES	WES
28	WES	CA, WES	CO, CA[B], RPI, SA, WES	CO, CA[B], RPI[B], SA[B], WES	WES
29	WES	CO, CA, SA[A], WES	CO[B], CA[B], RPI[B], SA[B], WES	CO[B], CA[B], RPI[B], SA[B], WES	WES
30	CO, CA, RPI[A], WES	CA, WES	CO, RPI, WES	WES	WES
31	CA, CO, RPI[A], WES	CA, WES	CO, RPI, WES	WES	WES
32	CA, CO[A], RPI[A], WES	CO, CA, SA[A], WES	WES	WES	WES
33	CA, CO[A], WES	CO, CA, SA[A], WES	WES	WES	WES
34	CO, CA, RPI[A], WES	CA, WES	CO, RPI, SA, WES	CO, WES	WES
35	CO, CA, RPI[A], WES	CA, WES	CO, RPI, SA, WES	CO, SA, WES	WES

Table 7 (Continued)

Research Thrust	Platform/ Container	Payload	Acceleration	Capacity	Complete Match To the Four Requirements
36	CO[A], CA, RPI[A], WES	CA, WES	CO, RPI, SA, WES	CO, WES	WES
37	CO, CA, RPI[A], WES	CA, WES	CO, RPI, WES	WES	WES
38	CO[A], CA, RPI[A], WES	CO, CA, SA, WES	CO, RPI, SA, WES	CO, CA, SA, WES	CO, WES
39	CO[A], CA, RPI[A], WES	CA, WES	CO, RPI, WES	WES	WES
40	CO, CA, RPI[A], WES	CO, CA, SA, WES	CO, RPI, SA, WES	CO, CA, SA, WES	CO, WES

Requirements were considered met *if the capability was within 15 percent of the requirement*, which represents no substantive degradation in capability.

CO - University of Colorado
CA - University of California at Davis
RPI - Rensselaer Polytechnic Institute
SA - Sandia National Laboratories
WES - U.S. Army Engineer Waterways Experiment Station, proposed centrifuge

[A] - Marginal
[B] - Only partial
[C] - The 16-ton requirement in Table 3 came from the modeling of models consideration for a prototype condition and, because the scale factor for mass is n^3, a small shift in the test series accelerations and/or dimensions will bring the payload within the proposed WES capabilities with no degradation in capability.